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Greenhouse designs for Mexico. Aguascalientes, Querétaro and Sinaloa

Anne Elings, Bas Speetjes & Nieves García Victoria

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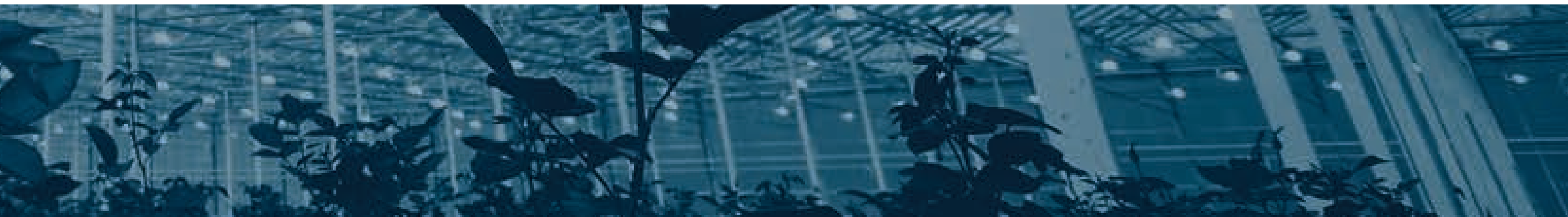

Referaat

Deze studie betreft de gevolgen voor wat betreft milieu en economie van de introductie van verschillende technologieën in de Mexicaanse staten Aguascalientes, *Querétaro en Sinaloa.* Zeven technologische niveaus werden geëvalueerd, van laag naar hoog, en variërend in kasdekmateriaal, verwarming, koeling, de aanwezigheid van schermen, het type substraat, het gebruik van recirculatie, en het gebruik van CO_2-verrijking. Productie neemt toe met toenemend technologieniveau. Waterverbruik neemt eveneens toe met toenemend technologieniveau (m.u.v. het hoogste technolgieniveau, de gesloten kas), net als energieverbruik (m.u.v. een kas met schermen en/of glazen kasdek) en de efficiëntie in watergebruik. Maar de efficiëntie in energiegebruik neemt af met toenemend technologieniveau (m.u.v. een kas met glazen kasdek). Het netto inkomen is in Aguascalientes en Querétaro het hoogst in geval een van kassysteem met glazen kasdek, en in Sinaloa voor systemen met verwarming, CO_2, verneveling en schermen. Als de meest simpele kastypen en het gesloten kastype buiten beschouwing worden gelaten (omdat ze een erg anders technologisch niveau hebben dan in Mexico gebruikelijk is), worden de verschillen in terugverdientijd klein. De terugverdientijd is in Sinaloa het kortst in het geval van een kas met recirculatie, verwarming en CO_2. De kansen voor de Nederlandse toeleverende industrie liggen op het vlak van de (verdere) introductie van recirculatie (waterbesparing), verwarming (productie, netto inkomen), schermen en glazen kasdek (energiebesparing, productie, netto inkomen), geothermie en zonnepanelen (hernieuwbare energie).

Abstract

This study reports on the environmental and economic impacts of greenhouses with different technological levels in the states of Aguascalientes, *Querétaro and Sinaloa in* Mexico. Seven technology levels were evaluated, varying in the type of substrate, covering material, heating, CO_2 enrichment, misting, screens, and the use of re-circulation. Increased technology results in increased production. With increased technology, water use increases (with the exception of the highest level of technology, a semi-closed greenhouse), energy use increases (with the exception of a greenhouse with a screen and a glass-covered greenhouse), water use efficiency increases, but energy use efficiency decreases (with the exception of a glass-covered greenhouse). Net income is highest for a glass-covered greenhouse for Aguascalientes and Querétaro, and for systems with heating, CO_2, misting and screens for Sinaloa. If the most simple and closed greenhouse for Aguascalientes and Querétaro are excluded (because they are very different technological levels), then pay-back periods for the remaining scenarios do not differ very much. The pay-back period for Sinaloa is shortest for a system with heating and CO_2. Opportunities for the Netherlands supply industry exist in the (further) introduction of recirculation systems (water saving), heating (production, net income), screens and glass greenhouse cover (energy saving, production, net income), geothermal energy and solar panels (renewable energy).

Extracto

Este estudio presenta el impacto económico y medioambiental de la producción hortícola en invernaderos equipados con tecnología diversa en los estados mexicanos de Aguascalientes, Querétaro and Sinaloa. Se evaluaron siete niveles tecnológicos (suelo o substrato, material de cubierta, calefacción, enriquecimiento carbónico, nebulización, pantallas térmicas, recirculación de agua). Un mayor nivel tecnológico redunda en un aumento de la producción pero también aumentan la demanda hídrica (con la excepción del invernadero semi-cerrado que representa el mayor nivel tecnológico) y la demanda energética (excepto con pantallas y vidrio como cubierta). Con el nivel tecnológico aumenta sin embargo la EFICIENCIA en el uso del agua, pero disminuye la eficiencia en el uso de energía (excepto en el invernadero de vidrio). El mayor beneficio en Aguascalientes y Querétaro se corresponde con el invernadero de vidrio; en Sinaloa, con el uso de calefacción, CO_2, nebulización y pantallas térmicas. En Aguascalientes y Querétaro el periodo de amortización de los distintos niveles tecnológicos es muy similar (si se excluyen el invernadero más simple y el más sofisticado). La amortización más corta se obtendría en Sinaloa con un invernadero equipado con calefacción y CO_2. Oportunidades para el proveedor Holandés: introducción de sistemas de recirculación del riego y drenaje (ahorro de agua y fertilizantes), calefacción (producción, ingresos), pantallas y cubiertas de vidrio (ahorro de energia, producción, beneficios), energia geotérmica y paneles solares.

Inhoudsopgave

Summary

Background: This study reports on the environmental (e.g., water, nutrients and energy use) and economic (e.g., production level, pay-back time of investments) impacts of the implementation of different technological modules under a variety of conditions, for the states of Aguascalientes, Querétaro and Sinaloa in Mexico. It is an elaboration of the study by Elings *et al.* 2013. The project wants to contribute to a more intensive collaboration between the Mexican and Dutch horticultural sectors.

Approach: The "Adaptive greenhouse" approach was followed, which defines a number of objectives (e.g., minimal water use, minimal energy use, high production, high product quality), required functions (e.g., energy use, heating, cooling, cultivation systems, crop protection systems, labour), possible greenhouse designs, and subsequently evaluates their sustainability on the basis of economic, water use and energy consumption parameters. The Kaspro greenhouse model, the Intkam crop model, and a financial model were used for quantification. Seven technology levels were evaluated, ranging from low to high-tech, and varying in covering material, heating, cooling, the presence of screens, the type of substrate, the use of re-circulation, and the use of CO_2 enrichment.

Production levels: The climate in Aguascalientes and Querétaro is suitable for horticultural production under protected conditions, however, heating in winter time, when temperatures are low, considerably lengthens the cultivation season and improves the production level. Also Sinaloa has a suitable climate. Production increase is realized through the day time use of CO_2 flue gasses from the heating system. Diffuse glass that realizes a better light transmission and distribution and thermal screens that realize higher temperatures in winter time in Aguascalientes and Querétaro or can protect against rare, but catastrophic, low night temperatures in Sinaloa, are further steps to increase yield.

Water use efficiency: Water use (m^3 m^{-2} y^{-1}) is reduced by the introduction of a recirculation system (and by a closed greenhouse that recoveres transpired water), while a heating system increases water use because the season is lengthend, and while a glass cover leads to increased crop transpiration (due to higher light transmission and better thermal insulation). Water use efficiency (kg produce per m^3 water) increases with increasing level of technology.

Energy use efficiency: Energy use (MJ m^{-2} y^{-1}) increases with increasing technology, with the exception of a system that use energy-saving screen, and a system that uses glass cover, that has better insulation properties than plastic cover. Energy use efficiency shows the reverse pattern. Prospects exist for the use of geothermal energy in for example Aguascalientes. Solar panels are obviously environmentally more sustainable than the use of fossil energy, however, their economic benefit is very situation-specific.

Economic sustainability: Investments and fixed costs increase with increasing levels of technology. The use of a heating system and fossil energy leads to higher variable costs, but also to higher production levels, higher income, and shorter pay-back period. Net income is highest for a glass-covered greenhouse for Aguascalientes and Querétaro, and for systems with heating, CO_2, misting and screens for Sinaloa. The pay-back period is lowest for the most simple greenhouse in case of the states of Aguascalientes and Querétaro, and for a greenhouse with recirculation, heating and CO_2 for Sinaloa. If scenarios the most simple and closed greenhouse for Aguascalientes and Querétaro are excluded (because they are very different technological levels), then pay-back periods for the remaining scenarios do not differ very much.

Implications for the supply industry: Opportunities for the Netherlands supply industry exist in the (further) introduction of recirculation systems (water saving), heating (production, net income), screens and glass greenhouse cover (energy saving, production, net income), geothermal energy and solar panels (renewable energy).

Resumen

Antecedentes: Este estudio presenta el impacto medioambiental (uso de recursos, agua y energía) y económico (producción, periodo de amortización de las inversiones) de la implementación de diferentes módulos tecnológicos bajo las condiciones climáticas y socioeconómicas reinantes en los estados Mexicanos de Aguascalientes, Querétaro y Sinaloa. Es una elaboración del estudio de Elings *et al.* 2013 . El propósito de esto proyecto es contribuir a una más intensa colaboración entre los sectores hortícolas mexicanos y holandeses.

Enfoque: El enfoque seguido fue el del “invernadero adaptativo”, por el cual se define una serie de objetivos (por ejemplo: el uso mínimo de agua, el uso mínimo de energía, alta producción, alta calidad de los productos) y de las instalaciones requeridas (calefacción, refrigeración, sistemas de cultivo, sistemas de protección de cultivos, mano de obra), los posibles diseños de invernadero, y, posteriormente, se evalúa su viabilidad en base a parámetros económicos y consumos de agua y energía. Para ello se combinan 1- El modelo Kaspro de invernaderos (físico) con 2- el modelo Intkam de cultivos (fisiológico), y con 3- un modelo económico. Se evaluaron siete niveles de tecnología que van desde baja a alta tecnología variando en el material de cubierta, la presencia de calefacción, refrigeración, pantallas térmicas, sustrato, y sistemas de recirculación y enriquecimiento por CO_2.

Niveles de producción: El clima en Aguascalientes y Querétaro es adecuado para la producción hortícola bajo condiciones protegidas. El uso de calefacción en invierno, cuando las temperaturas son bajas, alarga considerablemente la temporada de cultivo y mejora el nivel de producción. También Sinaloa cuenta con un clima adecuado; ahí el aumento de la producción se obtiene mediante el uso diurno de CO_2 procedentes de los humos de combustión del sistema de calefacción. Vidrio difuso que transmite más y mejor la luz, y pantallas térmicas que reducen la pérdida energética en invierno en Aguascalientes y Querétaro o pueden proteger contra las muy infrecuentes pero catastróficas bajas temperaturas nocturnas en Sinaloa, son otras medidas para aumentar el rendimiento.

Eficiencia en el uso del agua: El uso del agua (m^3 m^{-2} año^{-1}) se reduce gracias a la introducción de un sistema de recirculación (y en un invernadero cerrado que recupera el agua transpirada por el cultivo), mientras que un sistema de calefacción aumenta el consumo de agua debido a la prolongación de la temporada de cultivo. También la cubierta de vidrio conduce a un aumento de la transpiración del cultivo ya que transmite más luz y aísla mejor del frío. La eficiencia en el uso del agua (kg producto por m^3 de agua) aumenta a medida que aumenta el nivel de la tecnología.

Eficiencia energética: El consumo de energía (MJ m^{-2} año^{-1}) aumenta a medida que aumenta la tecnología, con la excepción de un invernadero equipado con pantallas de ahorro de energía, y uno con cubierta de vidrio, que tiene mejores propiedades de aislamiento que la cubierta de plástico. La eficiencia en el uso de energía muestra el patrón. Existen perspectivas para el uso de energía geotérmica en, por ejemplo, Aguascalientes. Los paneles solares son, obviamente, ambientalmente más sostenibles que el uso de energía fósil; sin embargo, su beneficio económico depende mucho de la situación.

Sostenibilidad económica: Las inversiones y los costos fijos aumentan con el aumento en nivel tecnológico. El uso de un sistema de calefacción por energía de origen fósil conlleva mayores costos variables, pero también conduce a los niveles de producción más altos, mayores ingresos y más corto período de recuperación de la inversión. El beneficio neto es mayor para un invernadero acristalado en Aguascalientes y Querétaro, y para sistemas con calefacción, CO_2, nebulización y pantallas térmicas para Sinaloa. El período de amortización es el más bajo para el más simple invernadero en el caso de los estados de Aguascalientes y Querétaro, y para un invernadero con recirculación, calefacción y CO_2 en el estado de Sinaloa. Si se excluyen los escenarios “invernadero más simple” e “invernadero cerrado” en Aguascalientes y Querétaro (porque son muy diferentes niveles tecnológicos), hay poca diferencia en el periodo de amortización calculado para el resto de escenarios (=niveles tecnológicos) considerados.

Implicaciones para los proveedores Holandeses de tecnología: Existen oportunidades para la industria de suministro tecnológico de los Países Bajos en la (mayor) introducción de sistemas de recirculación (ahorro de agua y fertilizantes), calefacción (producción, ingresos netos), pantallas y cubierta de invernadero de vidrio (ahorro de energía, producción, ingresos netos), energía geotérmica y paneles solares (energía renovable).

Samenvatting

Achtergrond: Deze studie betreft de gevolgen voor wat betreft milieu (bijv. water, nutriënten en energiegebruik) en economie (bijv. productie, terugverdientijd van investeringen) van de introducie van verschillende technologieën onder verschillende omstandigheden in de Mexicaanse staten Aguascalientes, Querétaro en Sinaloa. Het is een uitwerking van de studie uit 2013 door Elings *et al.* Het project wil bijdragen aan een intensievere samenwerking tussen de Mexicaanse en Nederlandse tuinbouwsectoren.

Aanpak: De “Adaptive greenhouse approach” werd gevolgd, waarvoor doelstellingen (bijv. minimaal watergebruik, hoge productie, hoge productkwaliteit), functies (bijv. energiegebruik, verwarming, koeling, het teeltsysteem, het soort gewasbescherming, arbeid), en mogelijke kasontwerpen worden geformuleerd, waarna de effecten op duurzaamheid worden geëvalueerd op basis van economische, watergerelateerde en energiegerelateerde parameters. Het Kaspro kasmodel, het Intkam gewasmodel en een financieel model warden voor de kwantificering gebruikt. Zeven technologische niveaus werden geëvalueerd, van laag naar hoog, en variërend in kasdekmateriaal, verwarming, koeling, de aanwezigheid van schermen, het type substraat, het gebruik van recirculatie, en het gebruik van CO_2-verrijking.

Productieniveaus: Het klimaat in Aguascalientes en Querétaro is geschikt voor bedekte teelt. Echter, in de winter is de temperatuur relatief laag en verlengt verwarming de teeltduur aanzienlijk, wat productieverhogend werkt. Sinaloa heeft ook een geschikt teeltklimaat. Productietoename wordt gerealiseerd door het gebruik overdag van CO_2 uit stookgassen van het verwarmingssysteem. Verdere productiestijging kan worden gerealiseerd met diffuus glas en energieschermen. Diffuus glas heeft een betere lichttransmissie en -verdeling dan plastic, en energieschermen realiseren een hogere temperatuur in de winter in Aguascalientes en Querétaro, en kunnen in Sinaloa beschermen tegen sporadisch voorkomende, maar catastrofale, lage nachttemperaturen.

Water use efficiency: Waterverbruik (m^3 m^{-2} y^{-1}) neemt af bij toepassing van een recirculatiesysteem (en in geval van een gesloten kas waarbij verdampingswater wordt teruggewonnen). Verwarming leidt tot hoger waterverbruik omdat het teeltseizoen wordt verlengd. Een glazen kasdek leidt tot een hogere gewasverdamping (vanwege de hogere lichtdoorlatendheid en hogere isolatie). De efficiëntie in watergebruik (kg’s geproduceerd per m^3 water) neemt toe met stijgend technologieniveau.

Energy use efficiency: Energieverbruik (MJ m^{-2} y^{-1}) neemt toe met toenemend technologieniveau, met uitzondering van een systeem met energieschermen, en een systeem met glazen kasdek dat beter isoleert dat een plastic kasdek. De efficiëntie in energiegebruik laat het omgekeerde beeld zien. Er bestaan mogelijkheden voor de toepassing van geothermische energie in bijvoorbeeld Aguascalientes. Zonnepanelen zijn meer milieuduurzaam dan het gebruik van fossiele energie, maar hun economische duurzaamheid is erg situatie-specifiek.

Economische duurzaamheid: Investeringen en vaste kosten nemen toe met stijgend technologieniveau. Het gebruik van verwarming en fossiele energie leidt tot hogere variabele kosten, maar ook tot hogere productie, hoger inkomen en een kortere terugverdientijd. Het netto inkomen is in Aguascalientes en Querétaro is het hoogst in geval een van kassysteem met glazen kasdek, en in Sinaloa in geval van systemen met verwarming, CO_2, verneveling en schermen. De terugverdientijd is in Aguascalientes en Querétaro het kortst in het geval het meest simpele kastype. Als de meest simpele kastypen en het gesloten kastype buiten beschouwing worden gelaten (omdat ze een erg anders technologisch niveau hebben dan in Mexico gebruikelijk is), worden de verschillen in terugverdientijd klein. De terugverdientijd is in Sinaloa in het geval van een kas met recirculatie, verwarming en CO_2.

Implicaties voor de toeleverende industrie: De kansen voor de Nederlandse toeleverende industrie liggen op het vlak van de (verdere) introductie van recirculatie (waterbesparing), verwarming (productie, netto inkomen), schermen en glazen kasdek (energiebesparing, productie, netto inkomen), geothermie en zonnepanelen (hernieuwbare energie).

1 Introduction

1.1 Background

Protected greenhouse horticulture in Mexico is growing strongly. Flowers are produced mainly for the domestic market, while there is much export of (fruit) vegetables to the USA and Canada (García Victoria *et al.* 2011). The level of technology varies from very low at a multitude of small farms to state-of-the-art in some agro-parks.

The Dutch industry is involved through the supply of planting materials, greenhouse installations, biological control agents, and knowledge. There is a strong interest to expand operations, as reflected in the strategy of individual companies and Greenport Holland International, which, amongst others, has resulted in the 2g@there programme MexiCultura. This programme focuses on 1) market demand, 2) professional knowledge transfer & cost benefit models, 3) Holland branding, 4) sustainability, 5) cooperation, 6) dialogue, 7) local presence, and 8) the Greenport model (http://www.mexicultura.com). Netherlands supply industry is most interested in collaboration with greenhouse companies that have adopted some level of technology, where it can make best use of its competitive advantage.

In the Mexican situation, increased sustainability requires interventions to improve the resource use efficiency of water and fossil energy, while at the same time the economic viability of farms and the sector as a whole must be guaranteed. Some interventions are technical, while others are socio-economic. A complex of interventions leads to a transition between technology levels. Transitions must be commercially viable and can be supported (or forced) by governmental measures. Technology transition paths are complex. Mexican growers realize that various modules (greenhouse constructions, water collection systems, pumps, computer systems, crop and pest management practices) have to be up-graded gradually, and that investments must be cost-effective. They also have to remain in balance, and improve e.g., environmental sustainability and product quality to better meet modern code of conduct requirements. On the whole, farm types move from low-tech farms that produce for the domestic market towards high-tech farms that produce for the export market, but this can not be considered as the development path for all farms. Technological levels and markets sometimes coexist in the same, bigger companies, depending on the achieved produce quality. In general, export orientated farms tend to be bigger. In this sense, it is important to note the high level of the fragmentation of Mexican farms: a small sized farm will be no bigger than 1 ha, while most medium sized farms will be 1 to 3 ha. A large farm can have an acreage of more than 10 ha.

A study on the horticultural sector was commissioned by the Dutch Agricultural Counsellor in Mexico (García Victoria *et al.* 2011). Greenhouse concepts were evaluated for the case of La Huerta, a farm in Aguascalientes (Elings *et al.* 2013). At a higher integration level, the further development of Horticultural Parks, AgroParks, or Metropolitan Food Clusters has been initiated at a number of places (e.g., van Mansfeld *et al.* 2012). A horticultural Park is a cluster of horticulture oriented companies that jointly strive for a more sustainable production situation. An Agropark combines a wider diversity of horticultural, agricultural, dairy, and other companies.

1.2 Project goal

The present study concentrates on the states of Aguascalientes, Querétaro and Sinaloa, which are all three important horticultural states. It is an elaboration of the study of Elings *et al.* (2013) that focused on the farm La Huerta in Aguascalientes, which is located within the perimeters of an envisaged Metropolitan Food Cluster (van Mansveld el al., 2012). Querétaro is the location of an AgroPark. While Aguascalientes and Querétaro are highland states, the state of Sinaloa has much lowland area with a very different climate.

The general project goal is to describe transition paths for Mexican greenhouse horticulture using actual data on weather and prices. More specific goals were to determine the environmental (e.g., water and energy use) and economic (e.g., production level, pay-back time of investments) sustainability of the implementation of different technological improvements. Tomato was chosen as example crop.

The project focused on the level of technology at Mexican side that matches with the Dutch supply and knowledge: mid- and high tech companies. The project touches upon the theme ‘climate smart agriculture’ because improved greenhouse designs can reduce the environmental impact (in Mexico: water foot print) of the greenhouse sector while providing sufficient produce for both local and international markets.

1.3 Acknowledgements

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2 Approach

2.1 Locations

Four locations in Mexico were selected for this study, viz. one in the state of Aguascalientes, one in the state of Querétaro, and two in the state of Sinaloa.

- Aguascalientes (Rancho Medio Kilo (La Huerta): 21°59’35.91”N 102°15’49.22”W)
- Querétaro (Agropark: 20°41’26.22”N, 100° 0’24.14”W)
- Culiacán (Sinaloa) airport: 24°45’51.54”N, 107°28’14.27”W
- Los Sitios (Sinaloa): 25°29’39”N, 107°38’26”W, 332 masl

The La Huerta farm is located at the Aguascalientes location, the Agropark is located at the Querétaro location, and the two Sinaloa locations were selected because of the relatively good quality of the weather data available. The Sinaloa locations are representative for a lowland and mid-altitude location, respectively.

Figure 1. Four locations for the scenario studies in this report (source: Google Earth).

The State of Aguascalientes knows an estimated acreage of 16 to 161 ha protected cultivation, depending on the survey (García Victoria *et al.* 2011), and is considering a Metropolitan Food Cluster (van Mansfeld *et al.* 2012). Protected cultivation in Aguascalientes is characterized by soil cultivation, plastic greenhouse covers, and water heating with gas. Geothermal energy is an option. Growers and other entrepreneurs in Aguascalientes have requested for support in the context of the Agrosfera project (van Mansfeld *et al.* 2012). The growers’ aim is to enlarge their business, participate in the agropark in which economic profitability, environmental sustainability, water use efficiency and a low carbon foot print are leading principles.

La Huerta.
Cosecha una vida saludable.

Rancho Medio Kilo belongs to Frigorizados La Huerta S.A. de C.V. [http://www.lahuerta.com.mx/] in Aguascalientes. Its director is Mr. Carlos Arteago Niepmann, and its Farm Manager is Mr. Roberto Javier Farfán Torres. Rancho Medio Kilo currently has 2 ha of greenhouses with plastic cover in which tomatoes “on the vine” are cultivated on soilless substrate.

Heating is realized with hanging gas heaters, and cooling with natural roof ventilation. Thermal screens and CO_2 enrichment are not available. New greenhouses with an acreage of 4.2 ha are under construction. Improvements will be realized in the form of hot water heating and fan-driven air circulation. The total farm acreage will increase to 6.2 ha. The farm is very much interested in improving its sustainability, *e.g.* through recirculation of drainage water (excess irrigation), improved water-use efficiency, and reducing its global foot print.

The State of Querétaro knows an Agropark of 800 ha, of which 100 ha are used for the high-technology production of sweet pepper and tomatoes. Greenhouses with glass cover have been constructed here. The park offers all necessary infrastructure such as water from underground sources, electrical power, natural gas, telephone, roads, security, etc. The companies pay for the common services but operate independently. Production levels for tomato are around 60 kg m^{-2} (García Victoria *et al.* 2011).

The State of Sinaloa knows an estimated area of 2500 - 3000 ha of greenhouses, generally of relatively low technological level, with tomato production levels of 12.4 - 21 kg m^{-2} (García Victoria *et al.* 2011). Greenhouse cover is made of nets or plastic, and although drip irrigation is wide-spread, little other technology has been adopted. There are two major concerns. Firstly, new agreements with the USA demand high quality tomatoes for export, which are relatively difficult to produce in nethouses. Secondly, continuity in production can not be guaranteed if the climate can not be controlled. A discussion on the need and options for, technological advancement has started.

2.2 “Adaptive greenhouse” approach

Greenhouse design depends on various parameters of which the most crucial ones are presented in Figure 3. The goal is to design a greenhouse that is economically feasible for a specific crop and given location. At the same time criteria such as water use efficiency, energy saving, and food safety can be considered. Using the adaptive greenhouse approach, greenhouse designs are evaluated and compared in terms of crop production, economics and resource use (efficiency) by varying installation parameters like heating, cooling, screening, covering etc. Depending on the market prices year-round production is considered. For every design the resources (energy, water, nutrients, labour, carbon dioxide) needed are calculated. The design also determines the level of food safety (reduced pesticide use) that can be achieved. The quality of labour is also directly related to the level of technology applied in the greenhouse design.

Three models were combined, viz.:

- The KASPRO greenhouse model;
- The INTKAM crop growth model;
- A financial model.

The “adaptive greenhouse” approach (Vanthoor, 2011) was followed, which consists of the following steps:

a. Identification of data sources: climate, production, water use, energy, prices, etc;
b. Definition of objectives: e.g., minimal water use, minimal energy use, high production, and high product quality;
c. Definition of required functions: e.g., energy use, heating, cooling, cultivation systems, crop protection systems, and labour;
d. Description of various economical greenhouse designs;
e. Description of transition paths. These transition paths not only include the greenhouse itself, but also knowledge, institutional infrastructure, post-harvest issues, etc;
f. Workshop with stakeholders in Mexico to increase awareness with the government and private sector, and define market opportunities;
g. Briefing of entrepreneurs in The Netherlands and Mexico, indicating market opportunities.

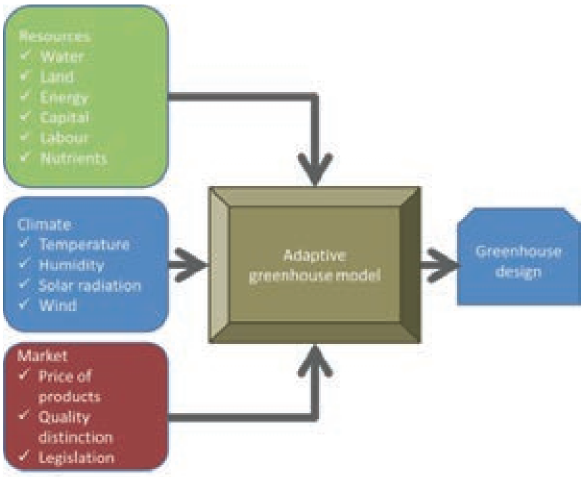

Figure 2. Schematic overview of the approach for the adaptive greenhouse calculations.

The KASPRO simulation model is based on physical equations describing the heat and mass fluxes associated with greenhouse plant production (De Zwart, 1966). A short description is presented in Annex 1. The dynamic simulations consider all heat and mass fluxes surrounding the greenhouse. A two-minute time step is used to calculate the dynamic process and recalculate all state parameters such as for example the greenhouse temperature. The greenhouse air temperature, canopy temperature, relative humidity, transpiration etc. are all calculated for a specific time period. All the resources used, such as water, energy and CO_2 are calculated. The production is also modelled in terms of dry matter production, which can be translated into fresh produce. The models have been validated with experimental data over the years and have been extended describing the economic implications (Vanthoor, 2011).

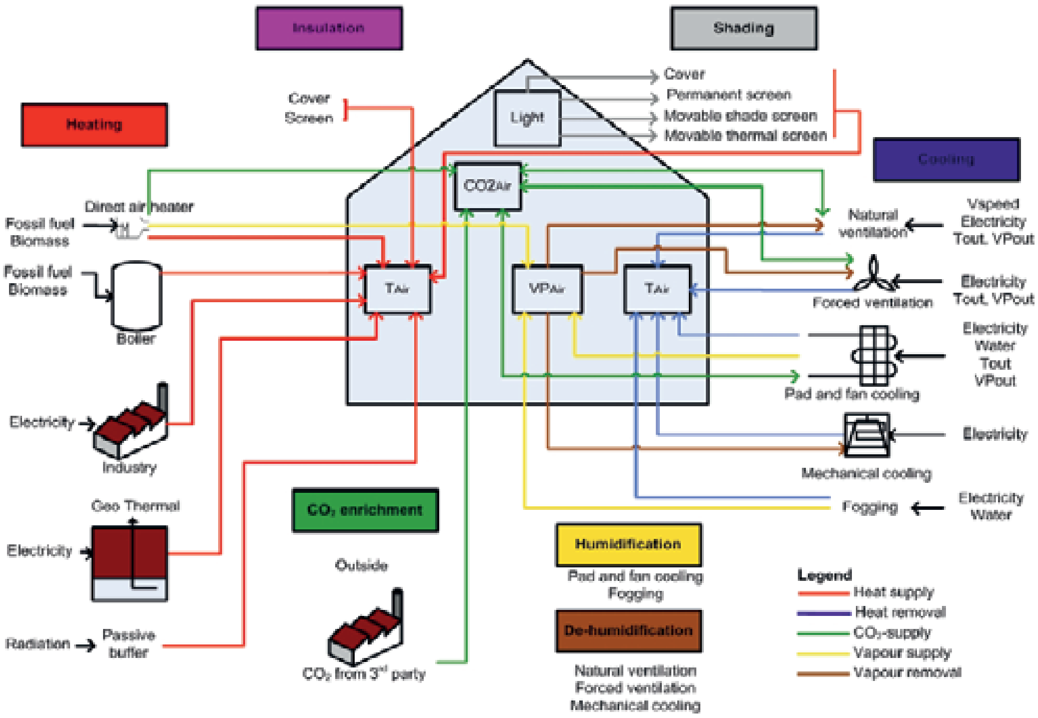

Figure 3. Visualization of the dominant fluxes and states used in the KASPRO dynamic greenhouse simulation model.

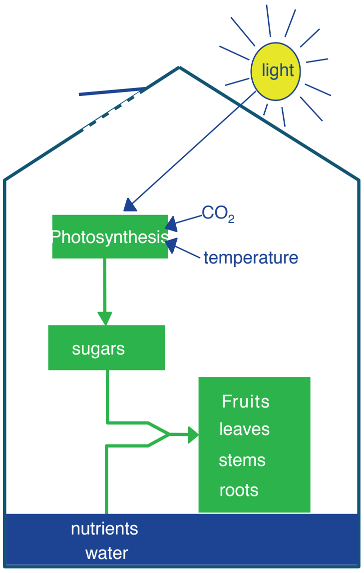

Figure 4. Visualisation of the Intkam crop growth simulation model.

The Intkam model simulates growth and development of a number of greenhouse crops, amongst others of tomato. Crop photosynthesis rate is computed at small time steps (5-60 min) with a biochemical model (Farquhar *et al.* 1980; Goudriaan, 1986) on the basis of radiation, CO_2, temperature and relative air humidity. Instantaneous rates are integrated to a daily crop photosynthesis rate. Daily dry matter partitioning and organ growth rates based on the sink strengths of various organs and assimilate availability (Marcelis *et al.* 2006). Crop transpiration rate is simulated in a similar manner. Intkam simulates the number of trusses (and fruits) on a daily basis, and the daily weight of harvested fruits. These processes also depend on the environmental conditions.

The financial model takes into account investment costs, interest rates, maintenance and depreciation costs, variable costs, market prices of tomatoes, and realized production. The model computes gross and net incomes, and pay-back period of the investments.

2.3 Scenarios

Seven scenarios were assessed, ranging from a naturally ventilated greenhouse where the crop is grown in the soil (scenario 1) to a greenhouse with all possible technologies (scenario 7). Scenario 2 is a multi-span greenhouse, covered with plastic film and with automated windows for ventilation. The crop is grown on substrate, and fertigation unit and drip irrigation are included. The technology level is increased by adding a heating system (scenario 3), a misting system for cooling (scenario 4), a shading/energy screen (scenario 5), and finally a glass roof and recirculation (scenario 6).

The climatic setpoints used are similar for all scenarios in order to make a proper comparison. Heating is used when the temperature drops below 16 °C. Ventilation windows open above 19 °C and this setpoint is raised linearly with 6 °C for 100 to 800 W m^{-2} of solar radiation outside (approximately 1 °C per 100 W m^{-2} solar radiation outside). The setpoint for relative humidity (RH) is set to 80%. If the RH increases, the windows are opened at a rate of 3% per 1% RH (for example, an indoor RH of 83% gives rise to a window opening of 9%). If both the temperature as well as the RH is above the setpoint, windows are opened to a point that corresponds to the largest calculated opening. The resulting indoor climates are presented in paragraph 3.2 and 3.3.

The greenhouse was assumed to be a multispan greenhouse with a gutter height of 3 m and a plastic greenhouse cover. The plastic film is assumed to be diffuse and to partly reflect infra-red transmission (for improved insulation). The exact properties of the film are given in Annex 3. The windows are movable and automated. Therefore, large windows may be used, which have realized a larger ventilation capacity in hot periods and can be closed in cold periods.

Scenarios 2-6 are the most realistic scenarios for Mexican horticulture. These scenarios have an increasing technology level, following a certain path of transition. The chosen path of transition is to some extent arbitrary. For example, we have chosen to first apply heating (scenario 3), followed by an energy screen (scenario 5). This sequence may very well be reversed, as is increasingly customary in The Netherlands. Also, recirculation may be introduced in scenario 5. More attention to the latter is paid in paragraph 3.5.

Figure 5. Cooling installation outside and inside the greenhouse needed to remove the heat in a closed greenhouse. This type of greenhouse is considered high-tech.

2.3.1 Scenario 1

Aguascalientes and Querétaro
The first greenhouse that was considered for Aguascalientes and Querétaro has a tunnel shape, and fixed ventilation openings of 15% of the ground surface. Ventilation opening may be changed by hand. In practice this only occurs twice per year, viz. at the start of summer and the start of winter. The cover is plastic, which could be white-washed during the summer months (to reduce heat load on the plants). Fertigation and heating systems are not available. The crop is grown in the soil, planted at the beginning of April and the crop cycle is ended at the end of October.

The winter months are too cold for tomato cultivation in an unheated greenhouse: crop development is too slow. We have tried to simulate a situation with open windows in summer and closed windows in winter; however, this resulted in day-time temperatures that were too high in winter, and too low night-time temperatures in summer. If windows are used, their opening must be flexible.

The position of the windows is changed from completely open (100%) to almost closed (5%) on March 2nd and October 30th. The greenhouse was empty from July 30th to August 28th.

Sinaloa
In Sinaloa, scenario 1 represents a net house, which is a simple structure that supports a net. The basic function of this net is to shield the crop from insects as well as extreme weather (especially wind). The structure is not water resistant and does not contain equipment to actively modify the climate inside like heating or ventilation systems.

2.3.2 Scenario 2

Scenario 2 is a multi-span greenhouse, covered with plastic film and with automated windows for ventilation. The crop is grown on substrate, and a fertigation unit and drip irrigation are included. Scenario 2 describes the current setup of, for example, La Huerta. Scenario 4 describes the newly constructed greenhouse.

2.3.3 Scenario 3

Scenario 3 differs from scenario 2 in the fact that it has a heating system with a heating power of 100 W m^{-2}, in combination with CO_2 enrichment. The heating system consists of a hot water boiler running on natural gas, where the heat is distributed by a pipe network of 5 pipes (51 mm) per span, and an upper heating net of 2.5 pipes with a diameter of 28 mm per span.

The main reason to favour this heating system over a system of direct gas burners is the fact that this system allows for accurate CO_2 enrichment by using the flue gasses from the boiler. Of course the flue gasses have to been clean enough to prevent them from causing damage to the crop, thus the burner has to be regulated. A heat storage buffer is needed to store the heat that is produced during the day, when the gas is burned and the CO_2 supplied to the greenhouse. The stored heat (hot water of 90 ^{o}C) is used at night time to heat the greenhouse. This type of enrichment is applied in the calculations using a heat storage buffer with a size of 100 m^3 per hectare of greenhouse, and the boiler is only running until the heat buffer is fully loaded (so no heat is wasted).

2.3.4 Scenario 4

Application of fogging (often referred to as misting) is gaining increased attention in horticulture worldwide. Especially in areas with high radiation intensities and low outside humidity, fogging contributes to a more favourable greenhouse climate, as it increases relative air humidity and lowers air temperature, which is favourable to the crop.

Fogging works along the same principle as the well-known pad-and-fan systems: dry air is cooled by evaporating water. The main difference between a pad-and-fan system and a fogging system is the fact that fogging is distributed more evenly through the greenhouse. Also, the electricity consumption of fogging installations is lower than that of ventilators in a pad-and-fan system that move large quantities of air through the greenhouse. In the simulations, a fogging system with a capacity of 300 grams of water per m^2 of greenhouse is assumed. The fogging is turned on when the RH in the greenhouse drops under 75%.

2.3.5 Scenario 5

Screens are applied in greenhouses for various reasons: reduction of sun radiation energy input during summer (shading), energy saving by reduction of heat energy losses during winter and cold nights, or both in combination.

Energy screen: Energy screens are used at night to increase the insulation of the greenhouse roof. This prevents heat loss, resulting in a smaller energy demand of the greenhouse. In the simulations, an energy screen is used that is transparent to light (similar to the Svensson SLS10 ultra plus screen). The screen is closed when the outside solar radiation drops under 5W/m^2 and the outside temperature is lower than 10 ^{o}C.

Shading screen: As radiation intensities in Mexico are quite high in summer some shading can be beneficial to the crop. Although shading may increase product quality and decrease risks of crop damage, limiting light levels will decrease the potential production. Therefore, a shading screen was not used in the results for scenario 5.

2.3.6 Scenario 6

In vegetable production, a rule of thumb states that *1% more light = 1% more potential production.* Of course this rule is only valid if all other growth factors (T, RH, CO_2, etc.) are not limiting and within the optimal ranges. However it is save to state that a greenhouse covering should allow the sunlight to enter the greenhouse as much as possible for a maximum potential production rate.

A glass cover has a higher transparency than a plastic greenhouse cover, especially when considered over several years (because the light transmission of plastics decreases due to ageing). More important, a glass cover can be cleaned easily as opposed to plastics. Whereas plastic is 40% diffuse for long-wave heat radiation, glass is not. The consequence is that air temperatures under glass are higher and that crop transpiration is higher as well

2.3.7 Scenario 7

Scenario 7 demonstrates the potential of a state-of-the art, closed greenhouse under Mexican circumstances. We realize that this greenhouse design is not likely to be implemented in practice, however it does give an ‘upper limit’ of greenhouse horticultural production. The greenhouse features a mechanical cooling system that is used to cool the air inside the greenhouse instead of opening the windows, diffuse glass cover, energy screens, etc. As a result, there is no air-exchange with outside, so CO_2 concentration inside is constantly around 1000 ppm. This, and the fact that the climate is always optimal for plant growth, enables very high production levels. Moreover, the closed greenhouse enables year-round production as the climate inside is always optimal for plant growth. In this greenhouse, we assumed a planting data of 15th of June and an end date of 1st of May.

Table 1. Overview of scenarios considered for Aguascalientes (A), Querétaro (Q) and Sinaloa (S).

Technology level	Description of the technology
1 (Q, A)	Fixed ventilation openings, plastic greenhouse cover, no fertigation system.
1 (S)	Net house; net cover (not waterproof), no active climate systems, fertigation system
2	Automated windows, substrate and fertigation unit
3	plus heating system, heating pipes, and CO_2 dosing from (natural gas) boiler
4	plus misting system for evaporative cooling
5	plus screening (single layer; SLS40/50)
6	plus a (normal) glass roof and recirculation
7	Closed greenhouse system with diffuse glass cover, mechanical air cooling and heating, energy screens, recovery of transpiration water, etc.

2.3.8 Irrigation system

Drip irrigation is a reasonably water efficient way of irrigation. Drip irrigation may be used with crops that are grown both in the soil (option 1) as well as in a substrate (option 2). The next step is to combine drip irrigation with water re-cycling (option 3). This is of course the most efficient way of irrigation in terms of water and nutrient use. The efficient nutrient use results in lower running nutrient costs, which balances the relatively high investment costs.

We have chosen for the following approach:

a. A drain fraction of 0.3 (or 30%) has been used for scenarios 1-5, which is an acceptable season-average drain fraction for a tomato cultivation system **without recirculation**;
b. A drain fraction of 0.1 (or 10%) has been used for scenario 6, which is a representative value of a tomato cultivation system **with recirculation**;
c. A recovery fraction of 0.4 (or 40%) has been used for scenario 7, which reflects 40% **recovery of the water** in the mechanical air treatment unit.

The impact of water recirculation in this study is therefore visible when comparing scenarios 5 and 6. Water recirculation can of course be introduced in earlier scenarios. This will not influence the production, but will influence the water use efficiency and the running costs.

2.3.9 CO_2

Increasing the level of CO_2 inside the greenhouse increases crop production. This is in principle possible in all scenarios, by installing a distribution system and connecting it to a source (pure / from boiler), provided such a source is available. The higher the ventilation rate, the lower the impact of CO_2 enrichment will be. We have assumed CO_2 enrichment for scenario's 2-7, based on the CO_2 that is produced by a boiler that runs to heat the greenhouse. An alternative is to use pure carbon dioxide for enrichment. The economic feasibility of the application depends on the price of the CO_2 and the price of the production. Since the price of CO_2 is not exactly known this option was not considered in this study.

2.3.10 Energy supply

For all scenarios, we have calculated the energy demand (thus, the total amount of heating energy that is needed to keep the required climate inside the greenhouse). The *source* of energy is discussed separately; gas burners are commonly used. However, we also assess more sustainable sources like geothermal energy, underground heat storage and solar thermal energy.

We could not conduct economic assessments, as the costs of various energy systems were not sufficiently clear.

2.4 Resources

Investments costs for greenhouse construction and installation were based on KWIN 2010 (Vermeulen *et al.* 2010), assuming that such costs in Mexico and Europe are similar. Possible lower costs due to for example lower labour costs are assumed to be counter-balanced by shipment costs for imported goods. Details are given in Annex 5.

The variable costs of the resources (Annex 2) were obtained from the management of the La Huerta farm (see Elings *et al.* 2013, and if not easily available, from KWIN 2010 (Vermeulen *et al.* 2010). It was assumed that variable costs of resources such as electricity and labour are the same across Mexican states, and that variable for costs of resources such as substrate and small items are approximately similar in Mexico and Europe.

2.5 Market

Products are sold on the domestic market as well as exported to the USA. The export prices are higher than domestic prices, however, the quality has to be higher as well. The prices used for the economic analysis are listed in Annex 2 and are based on the information provided by La Huerta for 2010 and 2011. The seasonal average is MX$ 17.9 (US$1.39).

Assessment of other data sources shows in a wide variation in tomato prices over months, over states and over years. We have assessed the consequences of variation by multiplying the default prices with a certain factor. The results of this are given in paragraph 3.9.2.

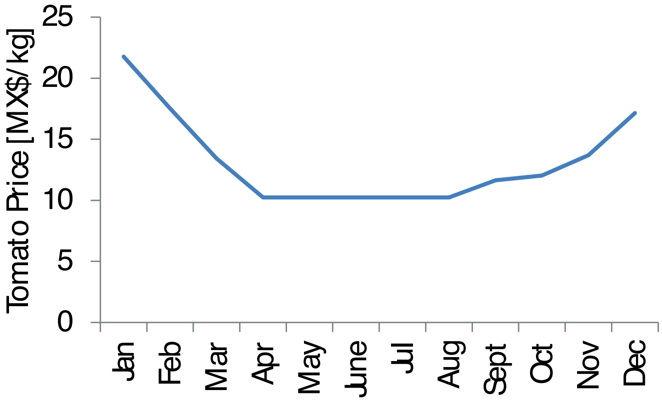

Figure 6. Prices used in the economic model. Source: Efrén M. Velázquez Calzada, Proyectos Estratégicos, Secretaría de Desarrollo Rural y Agroempresarial.

2.6 Climate data

Climatic data from Aguascalientes 2012 were provided by La Huerta for the simulation studies. For Querétaro, data were provided by HortiMaX, and for Sinaloa, data were obtained from the Centro de Investigación en Alimentación y Desarollo (http://www.ciad.edu.mx/clima/pc.asp). The data described the ambient conditions in terms of temperature, relative humidity and solar radiation.

2.7 Performance indicators

To compare the scenarios, a number of performance indicators were defined (Table 2.).

Table 2. Performance indicators used to compare the scenarios.

Performance indicator	**Dimension**	**Explanation**
Yield	kg m^{-2} $year^{-1}$	fresh fruit weight
Water consumption	kg m^{-2} $year^{-1}$	water used for irrigation and misting
Water use efficiency	kg yield kg^{-1} water	Production per kg of water
Energy demand	MWh	Heating demand + electricity demand; a 45% efficiency of electricity generation is assumed
Energy use efficiency	GJ kg^{-1} yield	Energy used for each kg of produce
Investment costs	Mexican $	Costs to build the greenhouse
Fixed costs	Mexican $ $year^{-1}$	Yearly costs associated with investments
Variable costs	Mexican $ $year^{-1}$	Yearly costs associated with farm operations
Net income	Mexican $ $year^{-1}$	Difference between gross income and costs
Pay-back period	year	Time period to earn back the investments

3 Results

3.1 Outdoor climate

3.1.1 Radiation

Solar radiation levels are a little higher in Querétaro than in Aguascalientes, with values of 7 to 7.5 GJ m^{-2} year^{-1}, respectively. Solar radiation in Sinaloa (approximately 5 GJ m^{-2} year^{-1}) is lower than in Querétaro and Aguascalientes, with Los Sitios in the highlands having higher radiation than Culiacán. Moreover, Culiacán shows a summer dip due to cloudiness during the rainy season. Compared to the solar radiation in The Netherlands (3.8 GJ m^{-2} year^{-1}), the radiation levels in Mexico are quite high. This results in high potential crop yields, as solar radiation is the main source of energy for the plants. Of course, this high yield potential can only be achieved if the other climate factors (temperature, humidity, CO$_2$ concentration, etc.) are optimal as well.

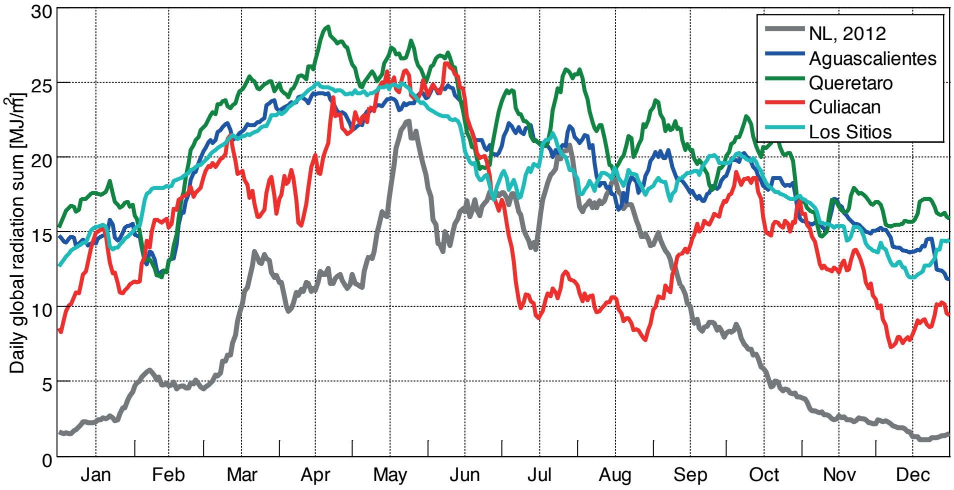

Figure 7. Smoothed daily radiation levels for Querétaro, Aguascalientes (2012) and Culiacán and Los Sitios (2011). The latter two locations are in Sinaloa. For comparison, radiation in The Netherlands (2012) was added.

3.1.2 Temperature

Temperature in Aguascalientes is slightly higher than in Querétaro, which is the reverse pattern in comparison with radiation. Winter temperatures in Aguascalientes and Querétaro drop below 15 °C, with occasionally sub-zero night time temperatures. Daily average temperatures below 15 °C were considered too low for tomato growth, resulting for un-heated greenhouses in a shortened growing season and therefore lower production levels (see Figure 8).

Sinaloa has a much warmer climate; especially the minimum temperature is relatively high with a summer daily averages of more than 25 °C. Temperatures in Culiacán are higher than in Los Sitios. Maximum temperatures exceed 35 °C. These are not optimal for crop growth, however, do not make tomato cultivation impossible.

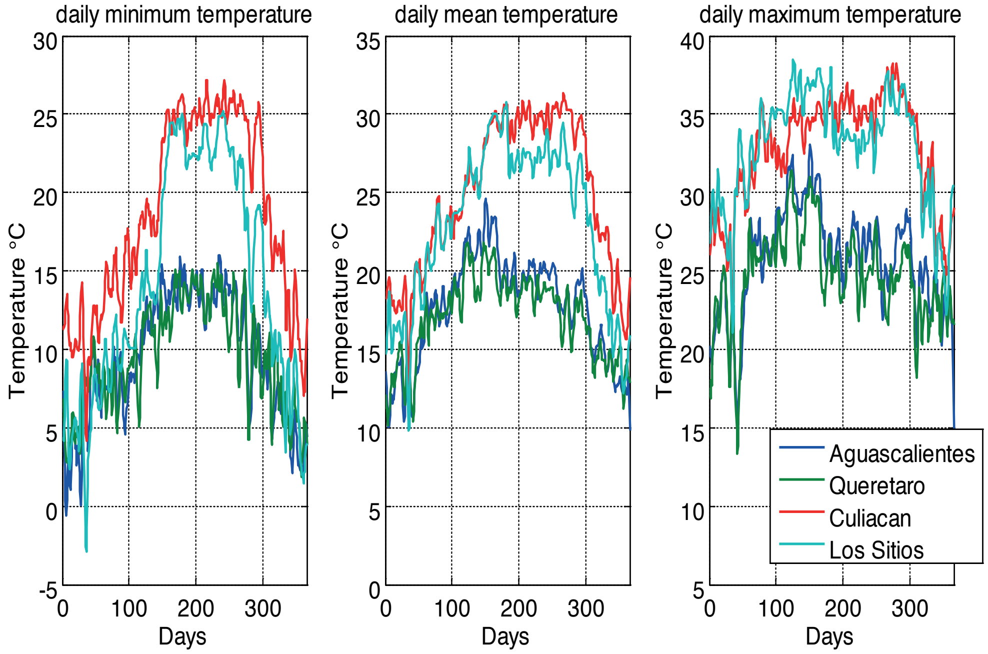

Figure 8. Temperatures at the four locations for 2012. The plot in the middle shows the daily average temperature, the left and right plot show the minimum and maximum daily temperatures, respectively.

3.1.3 Relative air humidity

Sinaloa has a more humid climate than the other two locations, which shows in the plots for daily mean and daily maximum RH (Figure 9.). Relative air humidity in Querétaro is slightly higher than in Aguascalientes, and in Los Sitios slightly higher than in Culiacán.

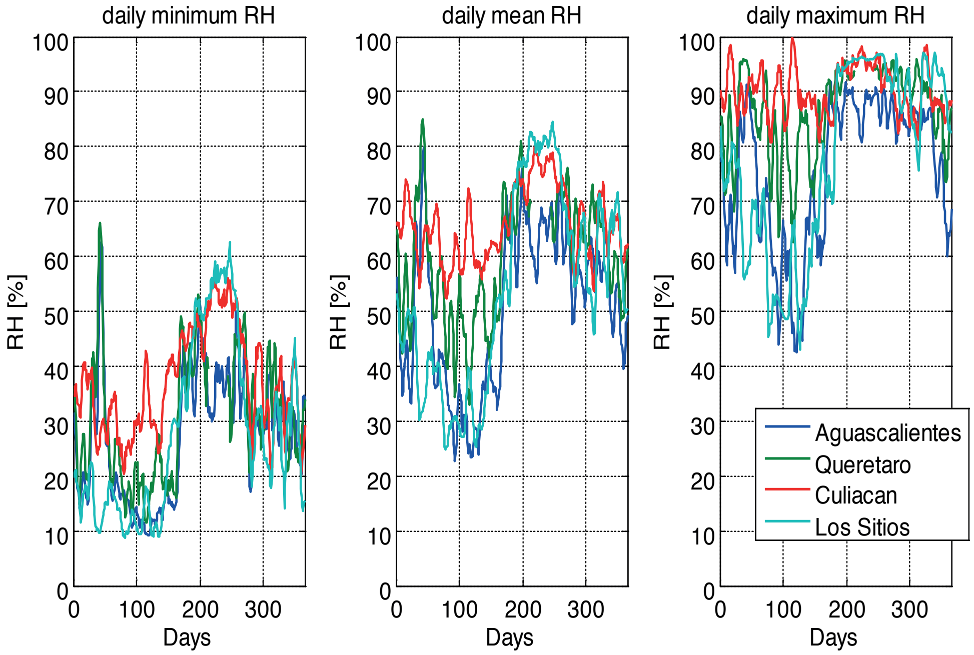

Figure 9. Relative humidity (RH) at the three locations for 2012. The plot in the middle shows the daily average value, the left and right plot show the minimum and maximum daily relative humidity, respectively.

3.2 Indoor climate Aguascalientes and Querétaro

The indoor climates are presented in the form of so-called duration load curves. A duration load curve is a Figure in which all (simulated) hourly values are sorted from high to low. In this way, it is possible to quickly check how often a certain situation occurs. For example, in Figure 10. we see that the temperature is higher than 12 °C for more than 4100 hours (follow the red arrow from the y-axis to the plotted blue line. Then follow the arrow to the x-axis to read the number of hours. The total number of hours on the x-axis is equal to the total simulation time; in this case the growing season from 15th of June till 1st of May.

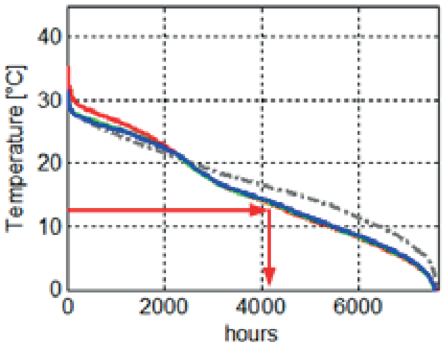

Figure 10. Example of a duration load curve.

3.2.1 Scenario 1; un-heated, simple, greenhouse

The air temperature in an unheated greenhouse in Querétaro is frequently lower than the ambient outdoor air temperature. The climate in the unheated low tech greenhouses in Aguascalientes and Querétaro is often too cold, which slows down the growth of the crop. We assumed a daily average temperature of 15 °C below which crop growth and development is too slow. Even though day-time temperatures may be sufficiently high to realize growth, daily average temperatures are too low to realize the formation of new trusses.

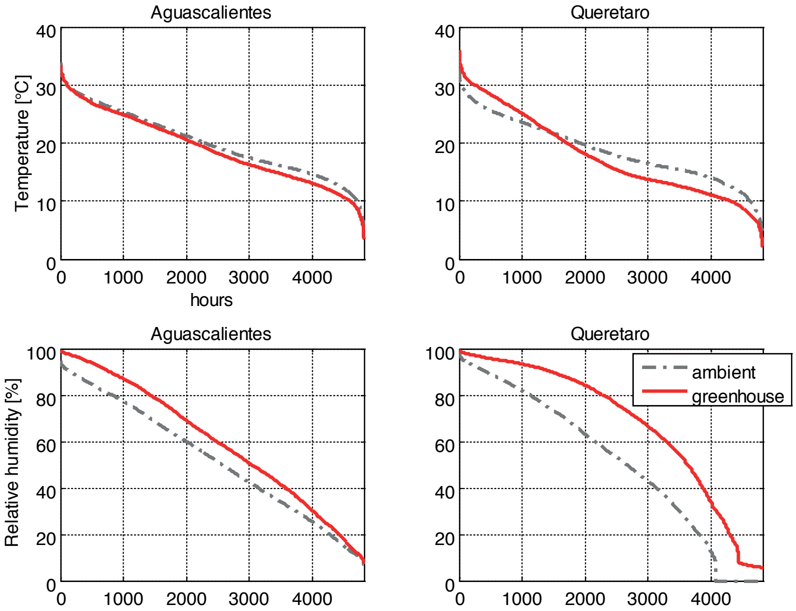

Figure 11. Duration load curves for temperature and relative humidity for an unheated greenhouse (scenario 1) in Querétaro (left) and Aguascalientes (right). The red line shows the climate inside the greenhouse, the grey dashed line is the ambient temperature / humidity.

A heating system is required to raise the greenhouse temperature in the states of Aguascalientes and Querétaro, and to lower the high levels of relative air humidity. This helps to prevent diseases.

The winter climate in an unheated greenhouse with fixed window openings is illustrated in Figure 12. Daytime temperatures reach 30 °C, however, night-time temperatures fall below 10 °C, especially in case of Aguascalientes.

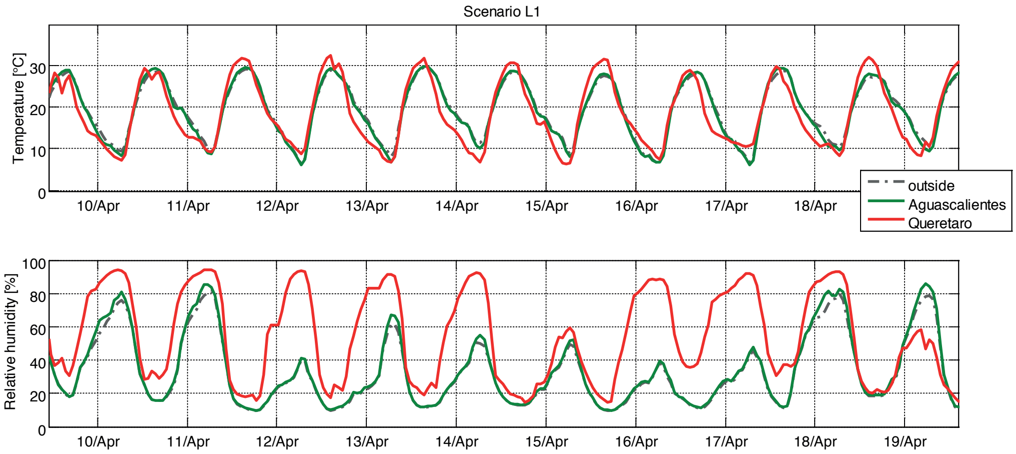

Figure 12. Illustration of air temperature and relative air humidity in an unheated greenhouse with fixed windows in spring.

3.2.2 Scenario 2; un-heated greenhouse

Scenario 2 is a greenhouse with motorized windows with opening that are controlled by a climate computer. The model mimics the behaviour of typical horticultural climate controllers as follows:

The ventilation setpoint is set to 19 °C, with a light increase of 6 °C in the trajectory of 100-800 W m^{-2}. This means that the windows start to open at 19 °C in the absence of solar radiation and will start to open at 19+6 = 25 °C if the solar radiation is higher than 800 W m^{-2}. The setpoint for relative humidity (RH) is set to 80%. Above this value, the windows will open 3% for every 1% the RH exceeds the set point.

Other climatisation equipment such as screens and evaporative cooling are not installed in scenario 2, but will be studied in the further scenarios.

Figure 13. shows the duration load curves for the greenhouse climate in scenario 2. Three different sizes for the (automatically controlled) windows were simulated. The main conclusion is that a 10% window opening is not enough for Querétaro and Sinaloa, as the maximum air temperatures reaches in those cases values that are too high. A window fraction of 50% (blue line in the figure) does not show much improvement compared to a 30% window opening (green line). Therefore, we recommend equipping the greenhouses with 30% window fraction, meaning that the area of the windows is 30% of the ground surface.

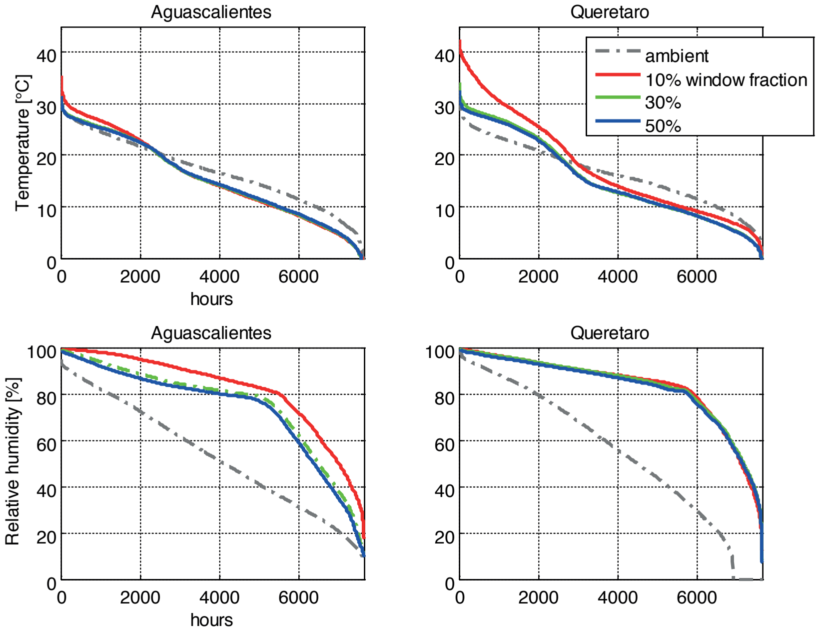

Figure 13. Duration load curves for greenhouse air temperature and relative humidity for three window fractions (10%, 30% and 50%) and three locations in scenario 2.

3.2.3 Scenario 3: automated, heated greenhouse

The heating setpoint is set to 16 °C, which means that the heating system switches on when the greenhouse air temperature falls below 16 °C. For sake of simplicity, the heating setpoint is constant; no variations during the day (e.g., a lower temperature in the first part of the night) and during the season (higher temperature in the first weeks after planting) were applied. The 'dead zone' between ventilation and heating is set to 3 °C, with a light increase of 6 °C in the trajectory of 100-800 W m^{-2}. This means that the windows start to open at 19 °C in the absence of solar radiation and will start to open at 16+3+6 = 25 °C if the solar radiation is higher than 800 W m^{-2}.

Figure 14. shows the effect of adding a heating system to an un-heated greenhouse. A system with a relatively low heating capacity (50 W m^{-2}) limits the number of hours with temperatures lower than 16 °C, especially in Querétaro. A larger heating capacity is better, though there is still a substantial number of hours during which the greenhouse air is colder than 16 °C (1500 hours in Aguascalientes and 700 hours in Querétaro). Further increasing the heating capacity improves this situation, however also the total energy demand rises sharply. A better option is to insulate the greenhouse better, by using energy screens (see scenario 5).

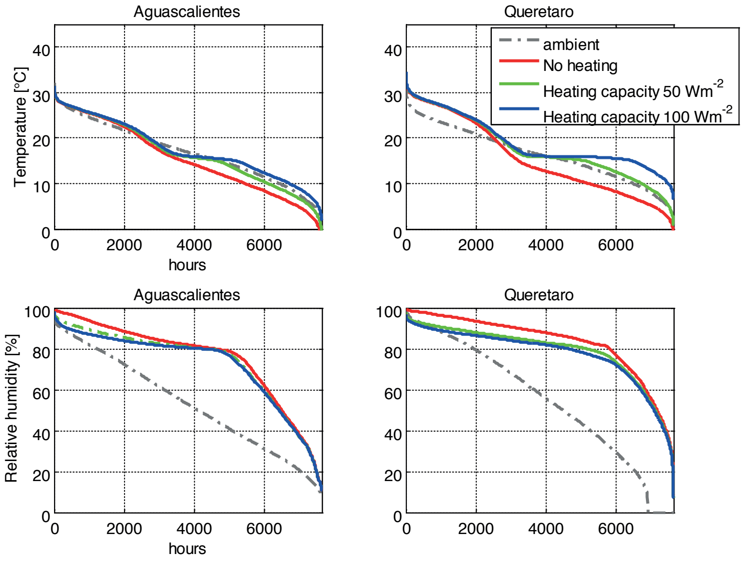

Figure 14. Duration load curves for greenhouse air temperature and relative humidity for three situations (no heating, 50 and 100 W m^{-2}) in scenario 3.

3.2.4 Scenario 4: heated, automated greenhouse with fogging

Figure 15. shows the duration load curves of situations with and without fogging systems. The fogging system switches on at 27 °C, which has consequences for the relative air humidity below approximately 60-70%. This decreases the maximum temperature in Querétaro. However, without fogging, maximum temperatures are not too high for a tomato crop, so the temperature effect of a fogging system in Aguascalientes and Querétaro is fairly limited. Of course a fogging system does allow a grower to control the minimum humidity inside the greenhouse. The limited effect of fogging on greenhouse air temperature and relative air humidity for Aguascalientes is shown for a few summer days in Figure 16. Air temperature is a few degrees lower around noon, and the relative air humidity is higher.

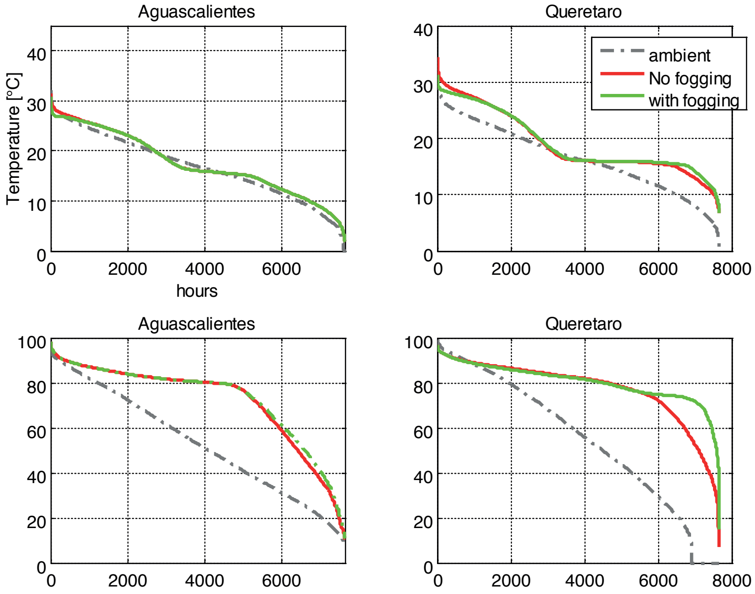

Figure 15. Duration load curves for greenhouse air temperature and relative air humidity for the situation with and without fogging installation for scenario 4. Note that only those parts of the curves are shown that are influenced by the use of fogging equipment.

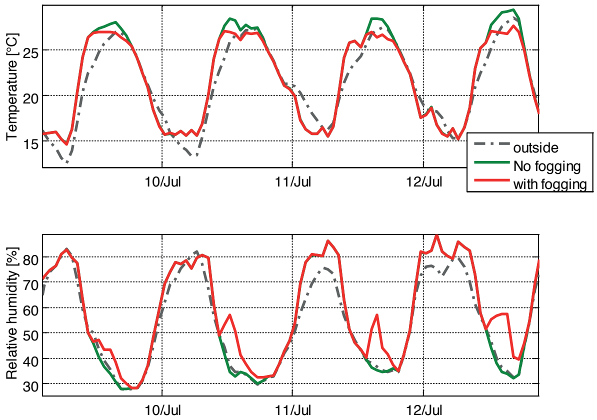

Figure 16. Illustration of the effect of fogging on three summer days (Aguascalientes). The fogging switches on at an indoor temperature of 27 °C. The humidity in the greenhouse becomes higher and the temperature lower than in the case without fogging.

3.2.5 Scenario 5: heated, automated greenhouse with energy screens

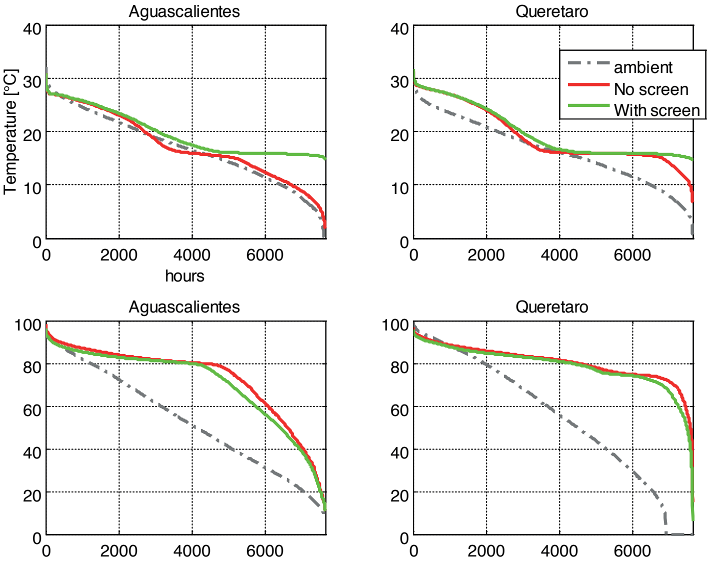

Figure 17. Greenhouse with and without energy screen that closes during cold nights to reduce heat losses.

Figure 17. shows the effect of an SLS10 Ultra plus screen that is closed at night (for insulation) . The effect of using an energy screen is observed at night; with a heating capacity of 100 W m^{-2}, the greenhouse without screen is not able to be kept at the setpoint of 16 °C. The most extreme temperatures are even as low as 5 °C. With an energy screen, the inside temperatures never drop below 15 °C.

3.2.6 Scenario 6: heated, automated greenhouse with glass cover

Glass has a better insulation value than plastic, mostly because it reflects long-wave heat radiation back into the greenhouse (instead of being partly transparent, as plastic films). The better insulation value results in a lower energy demand and a better climate inside in cold periods (Figure 18.). This property is good in case of cold nights, but less welcome in summer. As temperatures in summer are lower in a plastic greenhouse, both the fogging capacity as well as the plant transpiration are lower than in a glass structure (see also Table 3. and Table 4.).

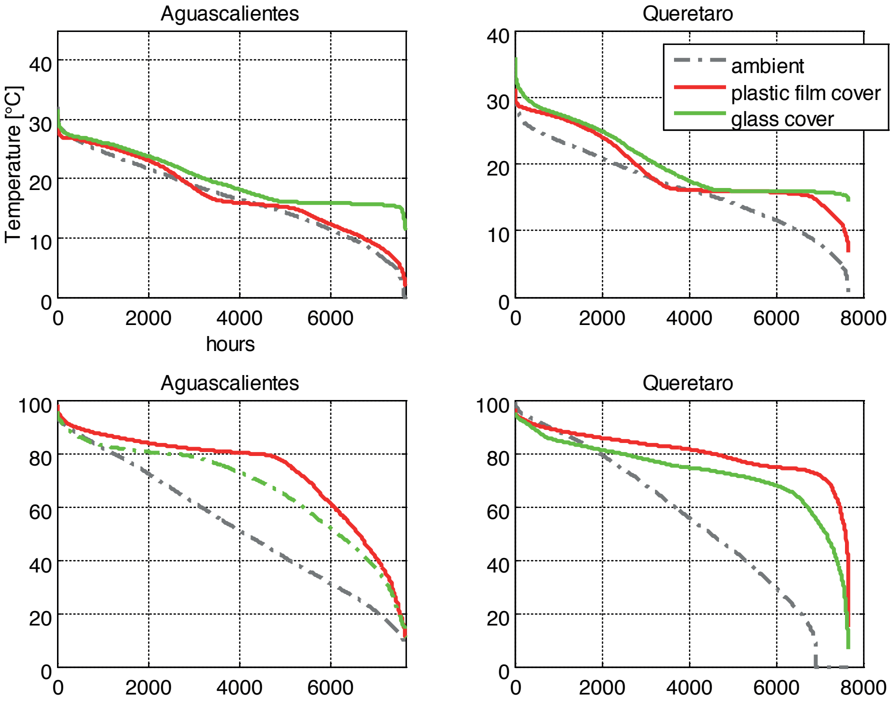

Figure 18. Duration load curves for greenhouse air temperature and relative humidity for the situation with plastic film or glass cover in scenario M5.

3.2.7 Scenario 7: high technology

Scenario 7 is a semi-closed greenhouse with a mechanical cooling system. The climate is controlled as good as possible, resulting in a high crop yield. Moreover, by cooling the greenhouse air the windows are hardly open, thus keeping the CO_2 inside the greenhouse. This results in a constantly high CO_2 concentration with a maximum value of 1000 ppm, which is favourable for plant growth.

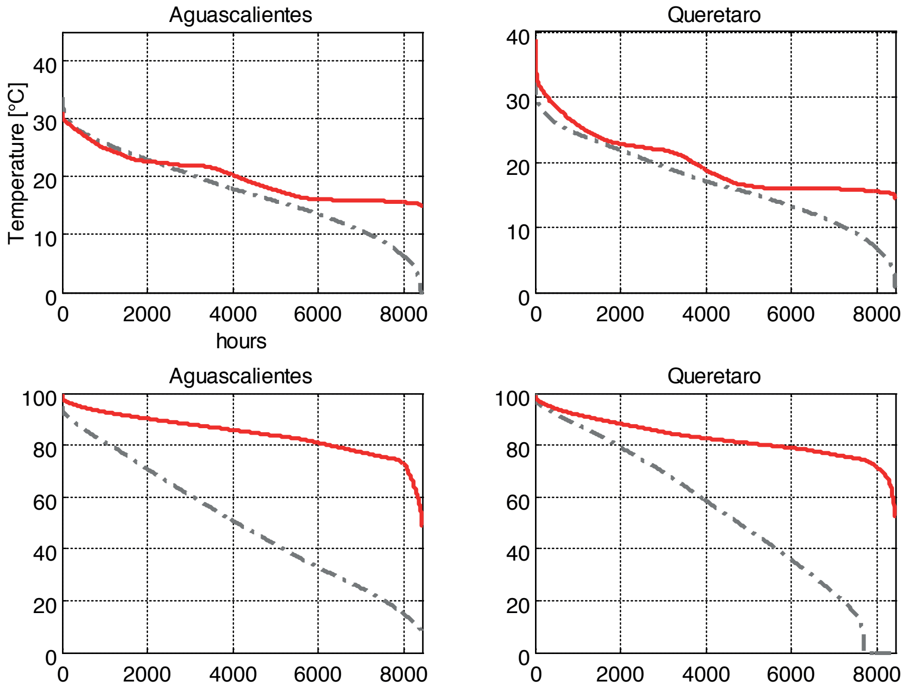

Figure 19. Duration load curves for a closed greenhouse (Scenario 7).

3.3 Indoor climate Sinaloa

3.3.1 Scenario 1: net house

Figure 20. shows that the temperature inside a nethouse is approximately similar to the outdoor temperature, however, that the relative air humidity is higher. This is due to the resistance for water vapour of the nets. A higher relative air humidity introduces the risk of infection by diseases such as Botrytis and mildew.

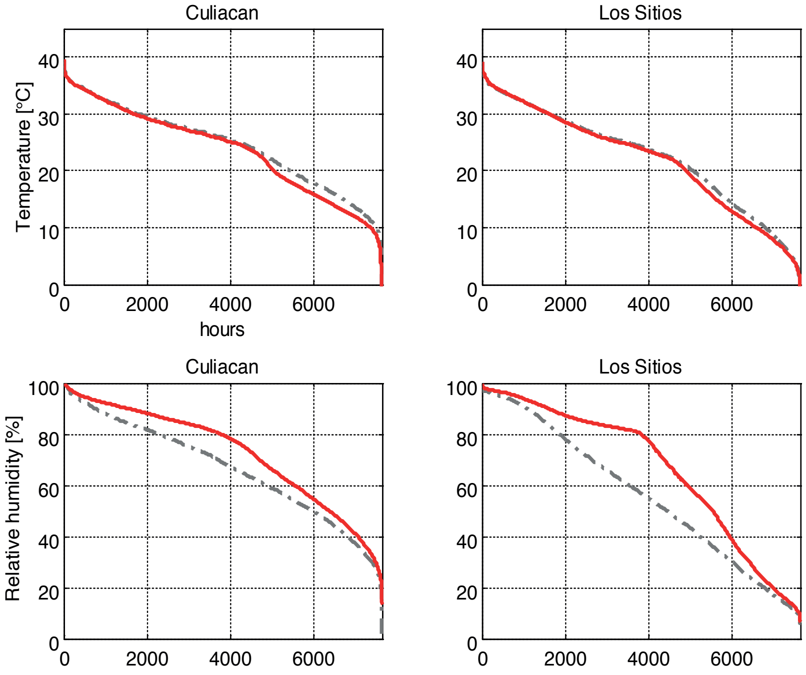

Figure 20. Duration load curves for air temperature and relative air humidity for the 2 locations in Sinaloa. The solid lines give the curves for the temperature/humidity in an unheated greenhouse. The grey dashed line is the ambient temperature/humidity.

3.3.2 Scenario 2: un-heated greenhouse

Figure 21. shows the duration load curves for the greenhouse climate in scenario 2. Three different sizes for the (automatically controlled) windows were simulated, viz. with window fractions of 5%, 30% and 50%. A window opening of 5% is not enough for Sinaloa, as the maximum air temperatures exceeds the ambient outdoor temperature. A window fraction of 50% (blue line in the figure) does not show much improvement compared to a 30% window opening (green line). Therefore, we recommend, just as for Aguascalientes and Querétaro, to equip the greenhouses with 30% window fraction, meaning that the area of the windows is 30% of the ground surface.

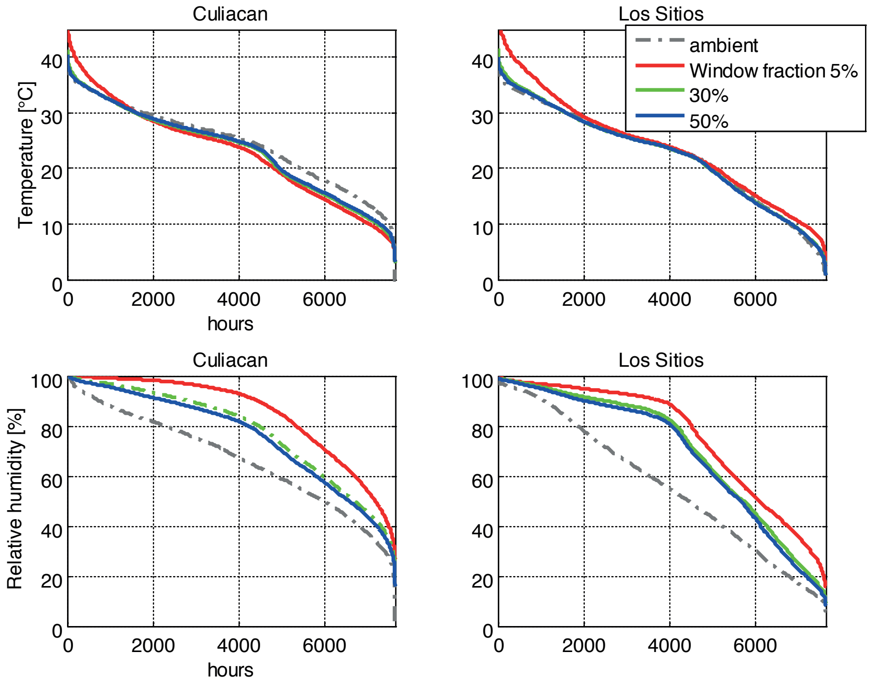

Figure 21. Duration load curves for greenhouse air temperature and relative humidity for three window fractions (5%, 30% and 50%) and two locations in scenario 2.

3.3.3 Scenario 3: heated greenhouse

Figure 22. and Figure 23. show that a heating capacity of 30 W m^{-2} is not sufficient to maintain greenhouse temperature above outdoor temperature if temperatures drop during cold nights, which is the case of the location of Los Sitios. A heating capacity of 80 W m^{-2} is required for this. The heating demand at lowland location of Culiacán is limited, and heating is less needed than at the higher altitudes of Los Sitios.

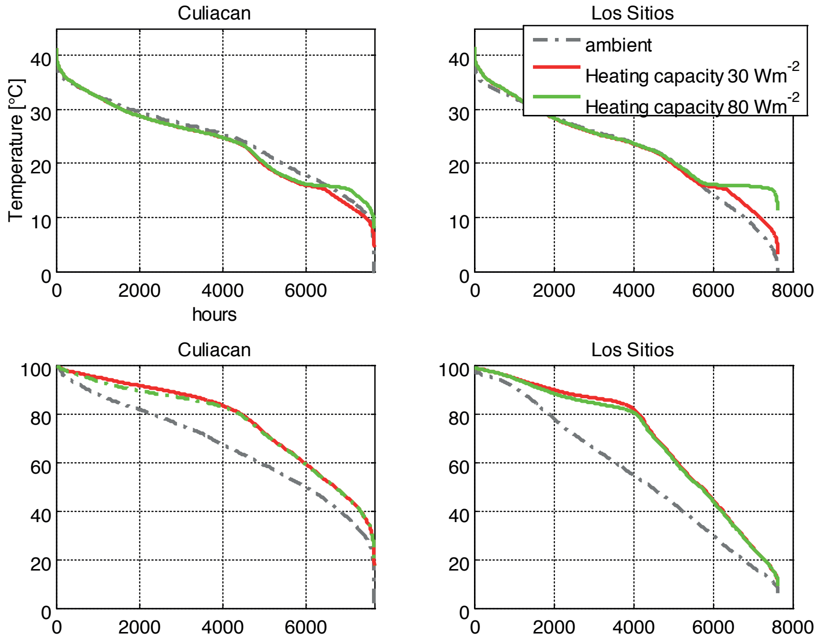

Figure 22. Duration load curves for greenhouse air temperature and relative humidity for three situations (no heating, 30 and 80 W m^{-2}) and two locations in Sinaloa for scenario 3.

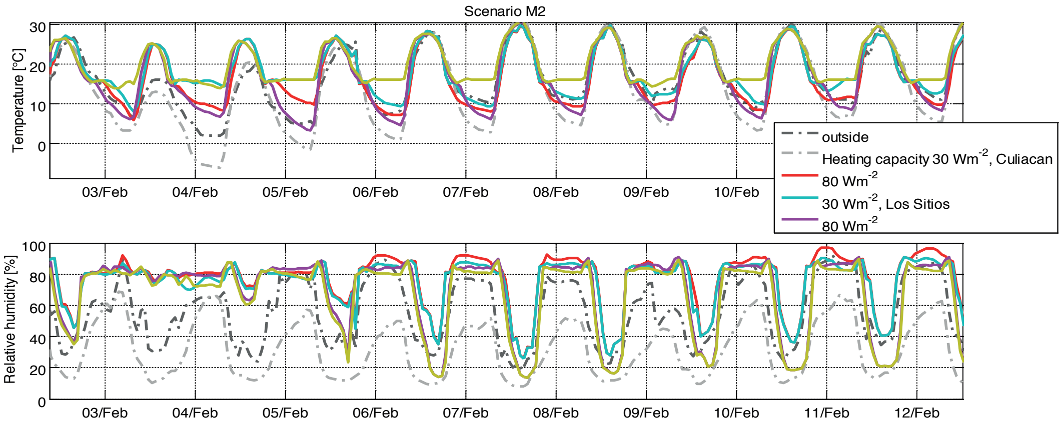

Figure 23. Climate inside a greenhouse in Los Sitios and Culiacán from 3 to 12 February.

3.3.4 Scenario 4: heated greenhouse with fogging

Figure 24. shows the duration load curves of situations with and without fogging systems. The maximum temperatures are reduced by using fogging, to levels below the ambient temperature. The relative humidity in the greenhouse becomes higher, but only at times when it was relatively low. The number of hours with high relative air humidity does not increase.

Figure 25. shows the effect of fogging on two hot summer days. The capacity of the fogging installation is chosen to be very high to show the effect.

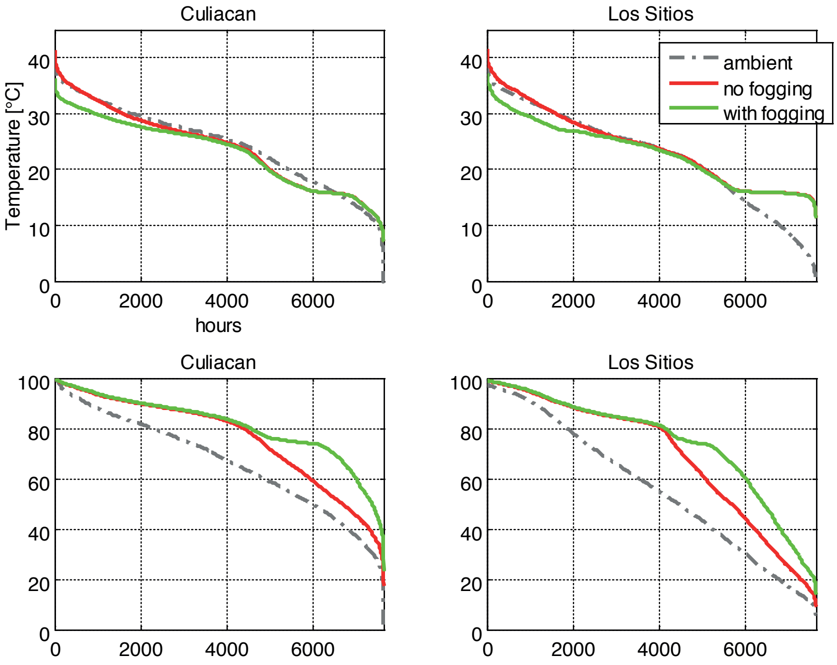

Figure 24. Duration load curves for greenhouse air temperature and relative humidity for the situation with and without fogging installation and two locations in scenario 4.

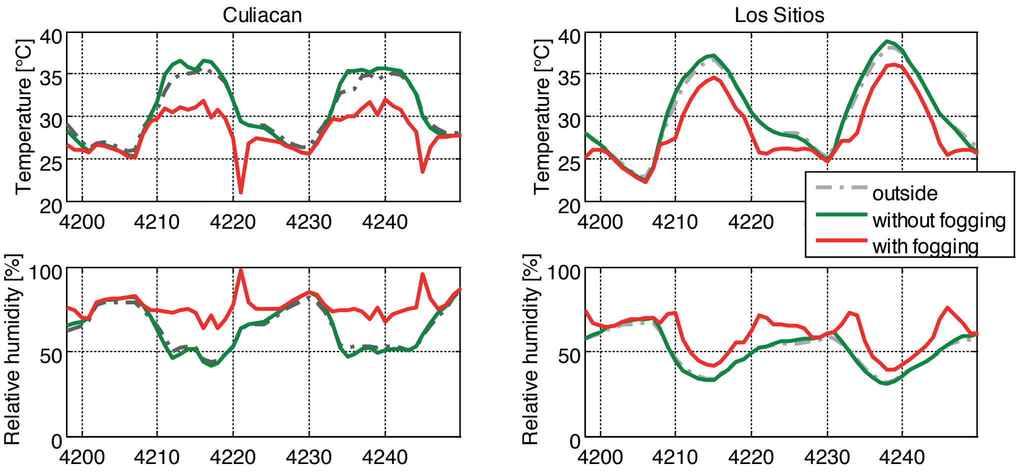

Figure 25. Illustration of the effect of extreme fogging on two summer days in Sinaloa. The fogging switches on at an indoor temperature of 27 °C and has a very high capacity of 900 grams/(m^{2}hour). The humidity in the greenhouse becomes higher and the temperature lower than in the case without fogging. (4200= 24th of June, 00:00u)

3.3.5 Scenario 5: heated, automated greenhouse with screens

Figure 26. shows the effect of an SLS10ultra plus screen that is closed at night (for insulation) and during day at high several solar radiation levels, in comparison with a plastic and glass greenhouse cover without screen. At day time, the use of a shading screen leads to *higher* temperature and RH levels. This may be counter intuitive; it is explained by the fact that the ventilation rate when using a screen is lower than the ventilation rate without a screen. This makes cooling, and especially fogging less efficient, thus increasing temperature and RH.

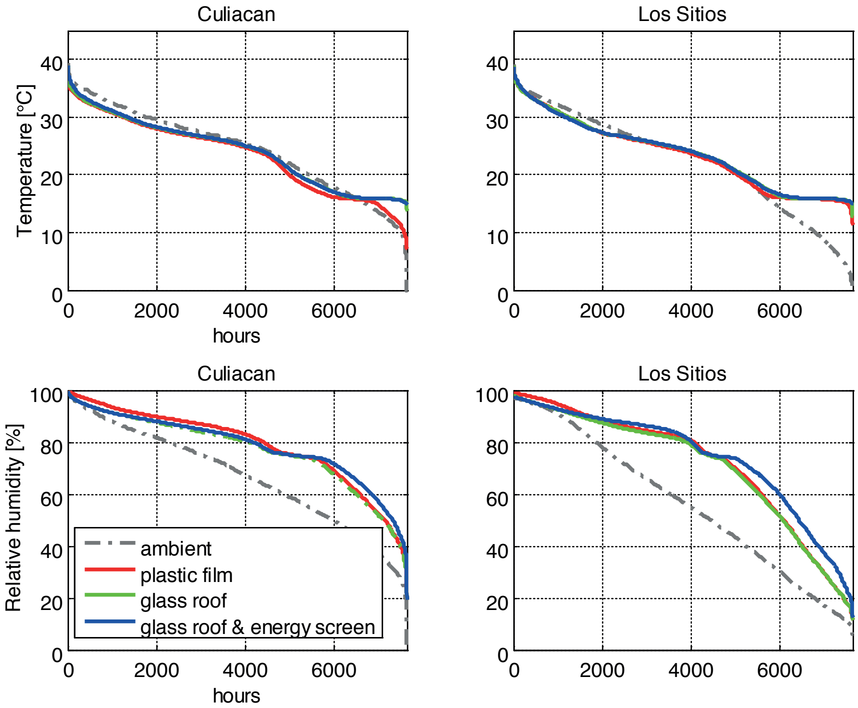

Figure 26. Duration load curves for scenario 5 with an SLS10 ultra plus screen that closes during cold.

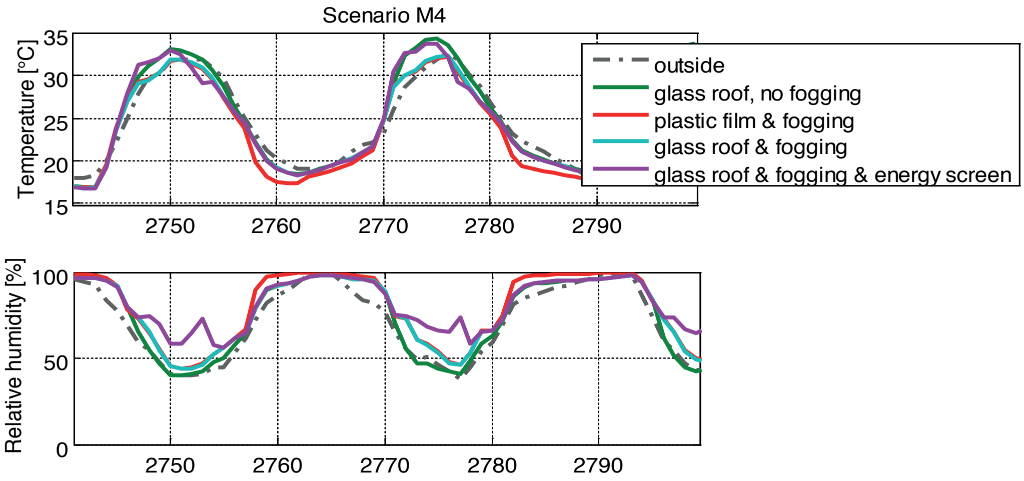

Figure 27. Comparison of the climate with fogging and/or shading screen (which closes at solar radiation higher than 500 W m^{-2}). A shading screen limits the ventilation rate, making fogging less efficient and causing the RH to go up during the day (purple line).

3.3.6 Cold nights

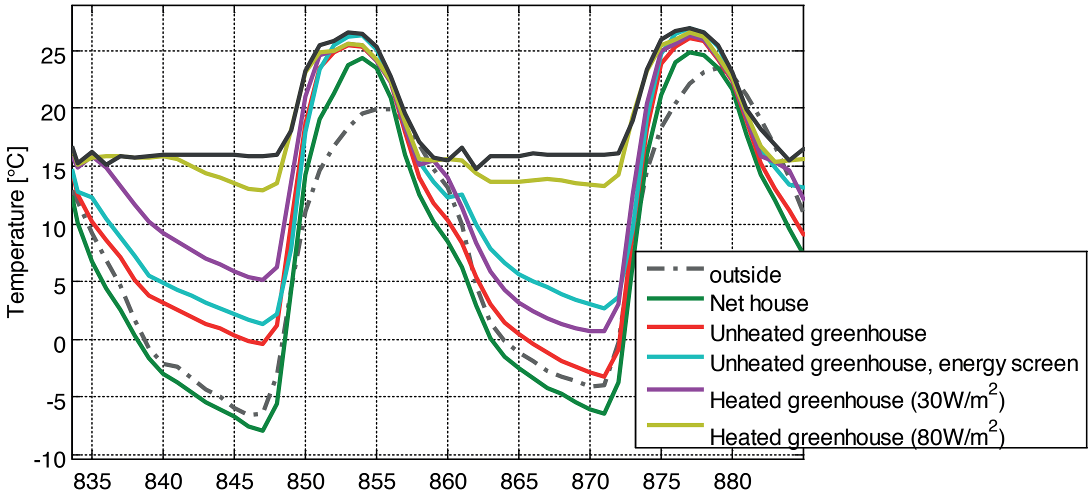

Figure 28. Comparison between heating and screening of a greenhouse at Culiacán in case outdoors temperature falls with 5 °C in comparison with the standard situation.

It may occur that night time temperatures in Sinaloa fall to very low values. This occurs rarely, but is nevertheless of concern to growers who may experience total yield loss. We assessed the situation in which the outdoor temperature was 5 °C lower than the standard situation (Figure 28.). This leads to the following conclusions with regards to night-time temperatures:

- Temperatures in a net house are a little lower than outdoor temperatures, due to the (low) evaporation of the crop and high radiative heat losses to the cold sky;
- Temperatures in an unheated plastic greenhouse are better than in a net house but do not prevent sub-zero temperatures inside the greenhouse;
- Temperatures in a heated greenhouse are always above 0 °C;
- An energy screen is very effective in raising temperatures, often better than a small heater (the frequency of 1 out of 2 in Figure 28. is not representative for the entire simulated period).

The ambient weather determines which of the two measures works best; an energy screen works well when radiative heat losses are high (thus cold sky, no clouds) and daytime temperature are high too (heat is stored and 'captured' in the greenhouse). A heating system is better at windy nights, as the effect of an energy screen is less.

3.4 Production and resource use efficiency

Table 3. to Table 6. show the estimated values for production, water use and energy use for the different scenarios. In order to make a comparison between the different scenarios the efficiency use of water and energy is given.

Table 3. Summary of production and resource use efficiencies for Aguascalientes. Results are graphically presented in Annex 4.

Greenhouse character	Dimension	Technology level						
		1	2	3	4	5	6	7
Fresh tomato production	kg m^{-2} y^{-1}	34.4	44.3	68.6	69.1	69.1	73.4	99.1
Water use	m^{3} m^{-2} y^{-1}	0.94	1.47	1.61	1.67	1.67	1.85	0.69
Energy use	MJ m^{-2} y^{-1}	20	38	1703	1703	1447	619	7003
Water use efficiency	kg m^{-3}	37	30	42	42	42	40	144
Energy use efficiency	kg GJ^{-1}	1695	1175	40	41	48	119	14

Table 4. Summary of production and resource use efficiencies for Querétaro. Results are graphically presented in Annex 4.

Greenhouse character	Dimension	Technology level						
		1	2	3	4	5	6	7
Fresh tomato production	kg m^{-2} y^{-1}	32.0	41.3	73.3	74.2	74.2	79.2	101.0
Water use	m^{3} m^{-2} y^{-1}	0.67	1.22	1.41	1.44	1.44	1.53	0.72
Energy use	MJ m^{-2} y^{-1}	20	39	1477	1302	1086	650	7852
Water use efficiency	kg m^{-3}	48	34	51	51	51	52	140
Energy use efficiency	kg GJ^{-1}	1562	1063	49	57	68	122	13

Tabel 5. Summary of production and resource use efficiencies for Los Sitios. Results are graphically presented in Annex 5.

Greenhouse character	Dimension	Technology level				
		1	2	3	4	5
Fresh tomato production	kg m^{-2} y^{-1}	19.7	25.6	59.4	60.4	60.4
Water use	m^{3} m^{-2} y^{-1}	2.15	1.92	2.00	2.46	1.91
Energy use	MJ m^{-2} y^{-1}	38	39	591	597	274
Water use efficiency	kg m^{-3}	9	13	30	25	32
Energy use efficiency	kg GJ^{-1}	516	654	100	101	221

Table 6. Summary of production and resource use efficiencies for Culiacán. Results are graphically presented in Annex 5.

Greenhouse character	Dimension	Technology level				
		1	2	3	4	5
Fresh tomato production	kg m^{-2} y^{-1}	16.4	21.6	50.5	51.3	51.3
Water use	m^3 m^{-2} y^{-1}	1.60	1.41	1.47	1.84	1.56
Energy use	MJ m^{-2} y^{-1}	35	37	611	615	256
Water use efficiency	kg m^{-3}	10	15	34	28	33
Energy use efficiency	kg GJ^{-1}	467	590	83	83	201

3.4.1 Querétaro and Aguascalientes

Fresh production for Querétaro is higher than that for Aguascalientes due to the higher radiation levels in Querétaro.

Production under heated conditions (scenario 3 onwards) is for Aguascalientes and Querétaro substantially higher than under un-heated conditions (scenarios 1 and 2). Due to low winter temperatures the growing season for scenarios 1 and 2 is shorter than for the other scenarios. Harvests in scenarios 1 and 2 are in the months July-October (planting mid-June, clearing early May), while in the other scenarios in the months October-April (planting in August).

Heating also allows for carbon dioxide enrichment, which has a very positive effect on production (scenario 3). The production increase due to evaporative cooling (scenario 4) is limited, since extremely high temperatures do not occur at this location, which makes the evaporative cooling less functional.

Production in a closed greenhouse system (scenario 7) is substantially higher than in open greenhouse systems. This difference is caused by the use of diffuse glass, which realized a better light distribution within the crop canopy, and the fact that the climate can be controlled optimally, especially regarding the carbon dioxide concentration.

We did not assess the impact of substrate cultivation (scenario 2) itself. It can be assumed that the move from soil to substrate cultivation can lead to a production increase of some 10% and better product quality, as substrate cultivation offers better opportunities for crop management.

It has been assumed that the plastic greenhouse cover is not brand new, and transmits approximately 40% of the long-wave radiation from within to outside the greenhouse. Glass cover (scenario 6) has a higher transmission coefficient than plastic cover, and therefore, the use of glass cover (scenario 6) leads to higher radiation levels within the greenhouse. Moreover, it does not transmit long wave heat radiation. The overall effect is that transpiration increases, that more fogging is required for temperature management, and that water use increases.

Also energy screens do not result in a change in production, as their effect on the climate (in particular, temperature) is at night time. Day time climate remains un-changed. The use of glass cover, however, does lead to an increase in production as a result of higher light transmittance (global radiation sum in a plastic greenhouse in Aguascalientes is 5.5 GJ, versus 6.0 GJ in glass greenhouse and 6.8 GJ outside.

It should be noted that all calculations assume ideal conditions (no diseases, etc.).

3.4.2 Sinaloa

Winter temperatures in Sinaloa are higher than in Aguascalientes and Querétaro, enabling year-round cultivation of tomato. The longer season results in higher production levels for scenarios 1 and 2. Due to the higher radiation levels at the higher altitude of Los Sitios, its production levels are higher than at Culiacán. Higher technology levels do not have much impact on simulated production levels, as day-time greenhouse climate does not alter much. If unusually cold winter conditions occur, screens (scenario 5) provide protection against low night temperatures (see paragraph 3.3.6).

3.5 Water

3.5.1 Water use efficiency

Water use (kg m^{-2} year-1) depends on the transpiration (1), the amount of drain water (2) and the amount of water used by the fogging system (3). Transpiration is mainly determined by the radiation and the relative humidity level inside the greenhouse (high radiation and a low RH result in a high transpiration). Drain water is the difference between the water amount given to the plants and the water amount used by the plants. Normally, drain is expressed as a percentage of the total water consumption, for example 30% drain. This means that for 1 m^3 of water is given to the plants, 0.7 m3 is used and 0.3 m3 runs off. The purpose of drain water is to ensure a homogeneous water and nutrient environment in the root zone; by giving more water than the plants use, small differences in drippers and substrate do not results in dry areas.

A fogging system uses water that is evaporated in the air. As a result, the air humidity becomes higher, thus lowering the plant evapo-transpiration, which partly counterbalances the water used by fogging. In this study, we assume 30% drain water for substrate and soil-bound cultivation. A percentage of 10% is used for a greenhouse with re-cycling of drain water (only possible in a substrate cultivation system). A fully closed greenhouse (Scenario 7) enables 40% recovery of condensation water in the cooling equipment, reducing the water use.

In Aguascalientes and Querétaro, the absolute water consumption is lowest in the simple greenhouse with ground-bound cultivation (scenario 1), because the growing season is shorter than the other scenarios). Water use in Aguascalientes is slightly higher than in Querétaro because of its higher temperatures and lower relative humidity inside the greenhouse.

In Sinaloa, the water use is much higher than in Aguascalientes and Querétaro because of the higher temperatures and lower relative air humidity. Fogging is used more often, which is reflected by the higher water consumption compared to a greenhouse without fogging.

Water use efficiency (kg fresh produce per m^3 water used) follows from the annual amounts of fresh production and water used. The water use efficiency increases with increasing technology level: more fresh weight of tomatoes is produced with the same amount of water. This pattern is only interrupted in case the growing season is shortened (scenarios 1 and 2 in case of Aguascalientes and Querétaro) and in case of fogging (scenario 4), which requires more water without additional production.

We also studied the effect of various water management systems on water use efficiency (Figure 29.). As an example, we chose scenario 3 in Aguascalientes, assumed the same production level for all situations, and only assessed the effects of a different water management system. Substrate cultivation results in 10% more production than soil production without a change in water use. Only recirculation results in reduced water consumption. Both the increased production (from soil to substrate) and the reduced water use (if recirculation is made possible) lead to an improved water use efficiency. The pay-back time increases if recirculation equipment is installed. If also the evaporated water is recycled, which is possible in a closed greenhouse but which is not possible in combination with scenario 3, then the water use efficiency further increases.

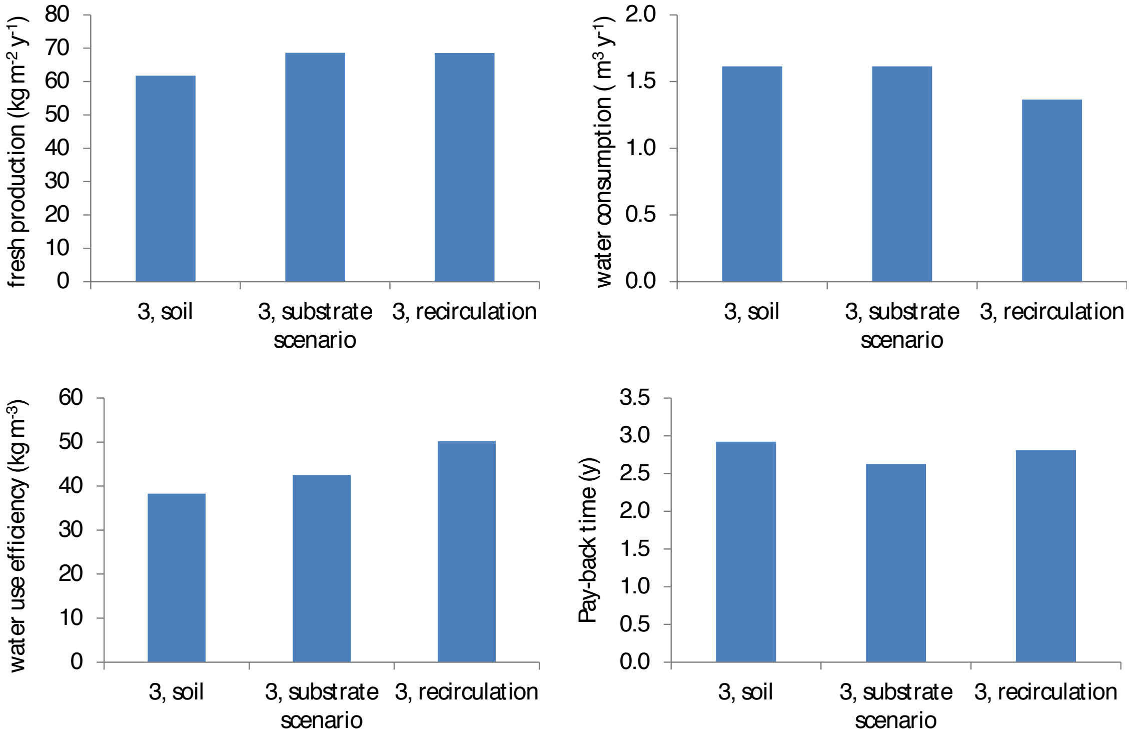

Figure 29. Effects of water management systems on water use efficiency, for Aguascalientes.

We have chosen to introduce recirculation of drain water in scenario 6. A grower may decide to introduce recirculation at a different technological level. The introduction of water recirculation technology results in lower water use, increased water use efficiency, but also requires higher investments. As water recirculation in itself does not lead to production increase, a longer pay-back time is the result. Figure 30. presents the results for Aguascalientes (data for Querétaro are similar) and Figure 31. for Culiacan (data for Los Sitios are similar). Recirculation is not possible for scenario 1 with soil cultivation, and the absence of recirculation does not fit in the concept op scenario 7.

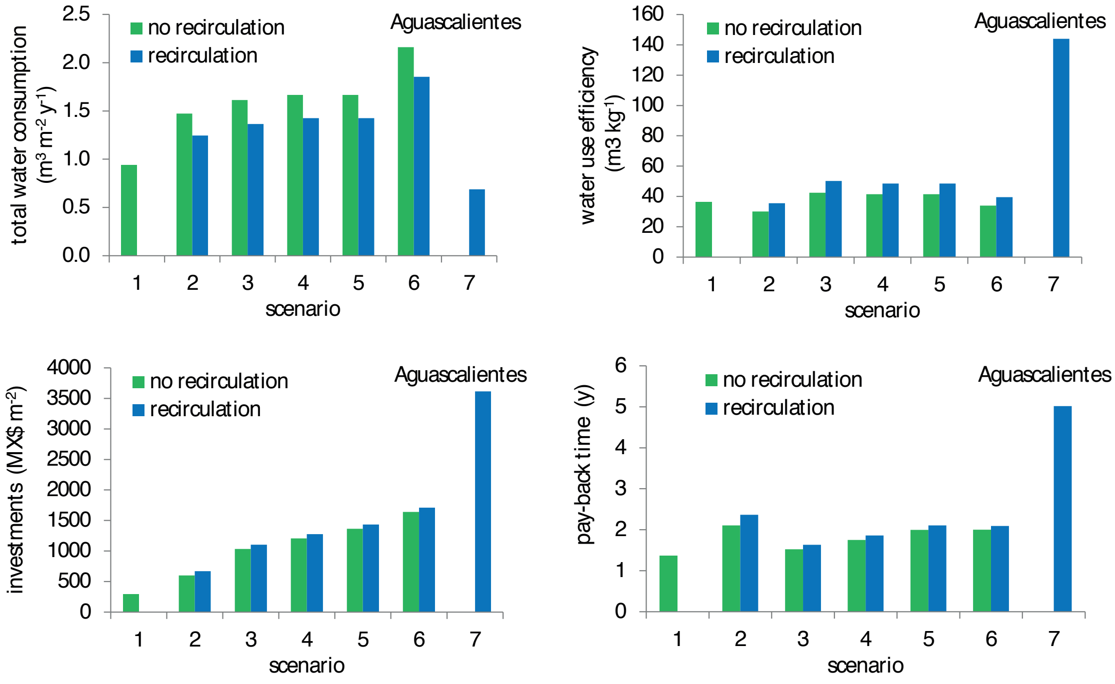

Figure 30. Effects of the introduction of recirculation on fresh production, water use efficiency, investments, and pay-back time, for Aguascalientes.

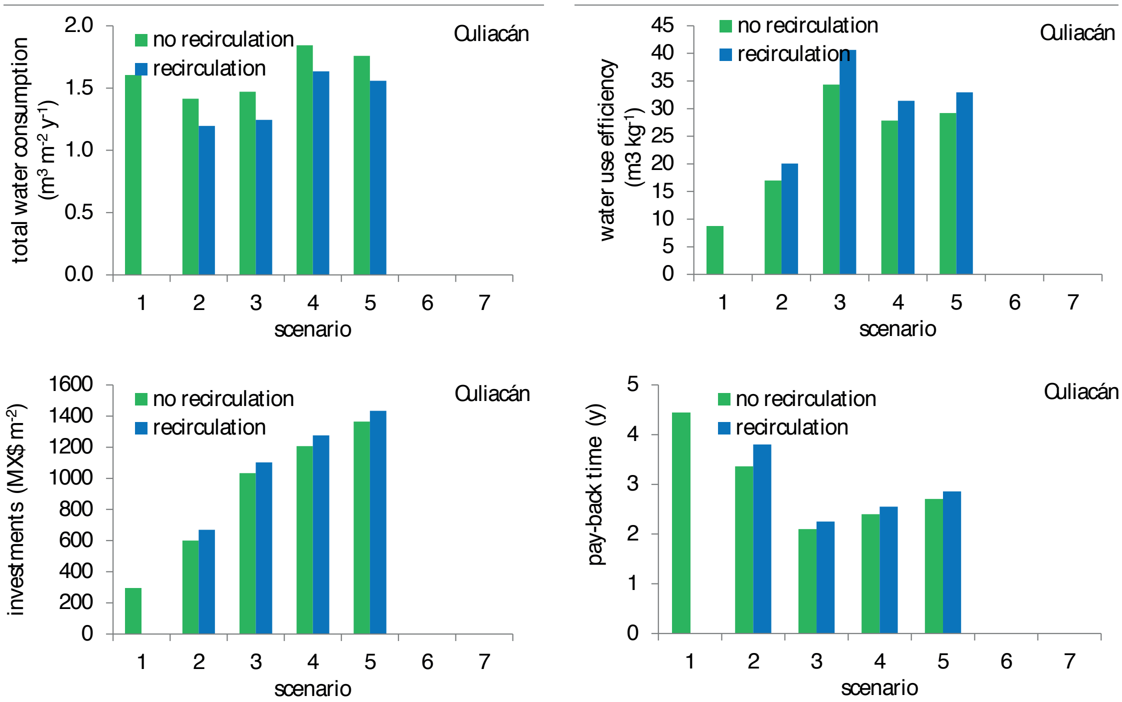

Figure 31. Effects of the introduction of recirculation on fresh production, water use efficiency, investments, and pay-back time, for Culiacán.

3.6 Energy

Energy use is relatively low in simple greenhouses, and much higher if energy is required for heating and for pumps to allow water recirculation. Mechanical cooling further increases the energy use.

Energy use is expressed in MJ m^{-2} y-1, so the heat source can be alternated. Geothermal heat, which is available in Aguascalientes, can also be utilized. Whether this heating source is a good alternative depends on numerous factors such as the temperature of the water from the well, the depth of the well, the method of discharging the return water, and minerals in the water. More information is needed to determine the economic potential of this heat source. But given the fact that warm water sources are not deep, the use of geothermal energy should have prospects.

Energy use efficiency shows a reverse pattern: it decreases as the technology level increases. The extra production does not keep pace with the extra amount of energy. This pattern is interrupted by the use of screens and by the use of glass greenhouse cover in Aguascalientes and Querétaro, where due to the better insulating properties a further reduction of heating energy is achieved.

3.6.1 Solar thermal energy

Solar energy is an alternative source for the greenhouse. The simplest system that is capable of collecting and utilizing solar energy consists of a solar collector, a buffer tank and a heating system inside the greenhouse.

Obviously, in a sunny climate as in Mexico, the yearly available solar radiation is much higher than the yearly heating demand of the greenhouse. So, if a buffer can be (economically) installed to store captured solar heat, the greenhouse can easily be heated (Figure 32, Figure 33.). However, long term storage of thermal energy requires large, well-insulated buffers, which are expensive and require a large ground surface. In this study we focus on relatively cheap collection and storage systems that use short term (maximum 2 days) storage of solar heat and a simple solar collector.

Figure 34. shows for the three studied states the daily solar radiation and energy demand of a greenhouse with 50 W m^{-2} heating capacity. Solar radiation of 0.5 to 0.7 m^{2} is enough to meet the heating demand of 1 m^{2} of greenhouse, which means that a solar collector of 50 to 70% of the greenhouse surface is able to provide enough heat to keep the greenhouse warm at all times.

Figure 32. Solar collector for greenhouse heating (left; www.certhon.com) and a heat storage tank (right).

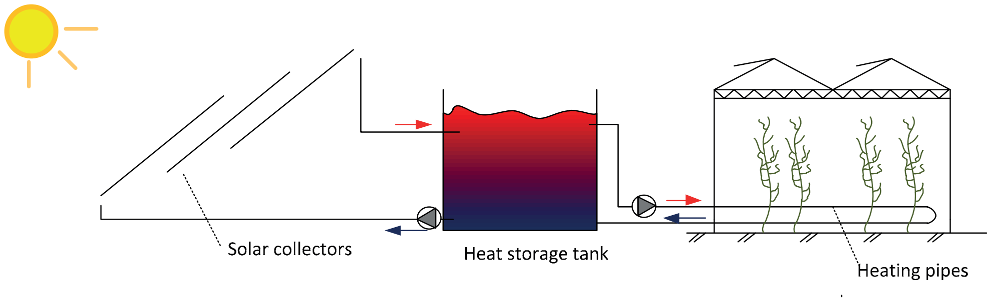

Figure 33. Layout of a solar thermal energy collection system

The consequences of installing solar panels are presented in Table 7. We assumed that a (simple) solar heat collector costs €10 m^{-2} collector. This is a collector on the ground, existing of hoses/pipes covered with a black plastic film. More advanced collectors, as in the Photo in Figure 32, have the benefit of higher efficiency at higher water temperatures. However, they are substantially more expensive. For the (additional) hot water storage tank and installations, we have assumed an investment of €4 m^{-2} greenhouse. The size of the solar collector depends on the heat demand of the greenhouse, the size of the storage tank and the required coverage ratio for solar energy. Using a fuel boiler to help reduce the peak energy demands will greatly limit the size (and thus the price) of the solar collector. For this study we chose a collector size of 0.6 m^{2} collector per m^{2} greenhouse for scenario 5 (plastic film greenhouse) and 0.5 m^{2} collector per m^{2} greenhouse for scenario 6 (glass greenhouse).

Solar panels reduce the primary energy demand and resulting running costs but increase investment costs. The overall balance is that the income increases in case of scenario 5, but decreases in case of scenario 6. Pay-back time is shorter in case of scenario 5 in Aguascalientes, remains un-changed in case of scenario 5 in Querétaro, and increases in case of scenario 6. The overall picture that emerges is that solar panels may or may not be economically beneficial, depending on the details of the greenhouse system. They are obviously environmentally more sustainable.

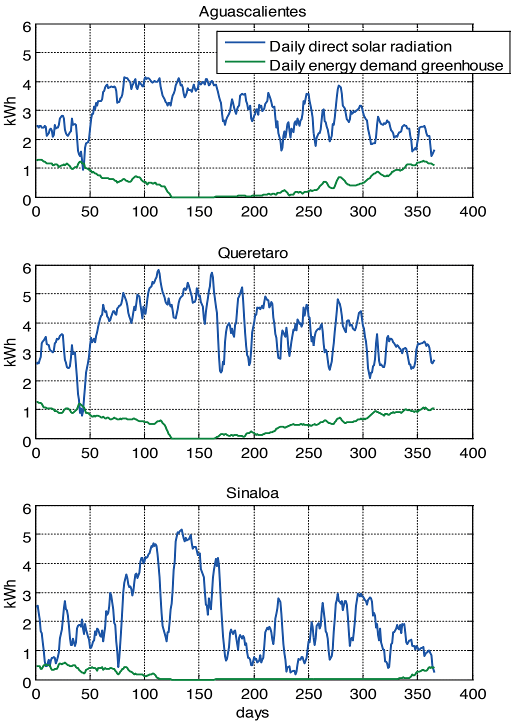

Figure 34. Daily solar radiation and daily energy demand of 1 m^2 ground surface and greenhouse area.

Table 7. Economic consequences of installing solar panels (S) for scenarios 5 and 6 in Aguascalientes and Querétaro.

Location	**scenario**	**Primary energy demand [MJ]**	**Investments (\$ m^{-2})**	**Income (\$ m^{-2} y^{-1})**	**pay-back time (y)**
Aguascalientes	5	1447	1364	292	3.1
	5 S	79	1536	416	2.6
	6	619	1710	555	2.4
	6 S	79	1874	487	2.8
Querétaro	5	1086	1364	451	2.3
	5 S	79	1536	489	2.3
	6	650	1710	633	2.1
	6 S	79	1874	572	2.4

3.7 Nutrients

Nutrient use was not part of this study. It forms, however, an important part of the running costs. In general, it is fair to assume that the amounts of nutrients used, and the nutrient use efficiencies approximately follow the pattern of water use and water use efficiency, respectively. Higher levels of technology require larger amounts of water, but the increased levels of fruit production (or, more correctly, higher biomass production) also require larger amounts of nutrients. Recirculation leads both to lower amounts of water and nutrients used.

3.8 Environmental sustainability

The optimal design in terms of sustainability depends on the weighting factors used on the factors listed in Table 8.

Water use per m^2 greenhouse decreases with technology level, and as the production per m^2 greenhouse increases with technology level, the water use efficiency is highest for higher technology levels. This is an important consideration, given the fact that water resources are limited, especially in the states of Aguascalientes and Querétaro.

The production increase per m^2 greenhouse causes an increased use *by the crop*, in absolute terms, of nutrients per m^2 greenhouse. However, as long as water and nutrients are drained to the outside environment, any system can not be considered really sustainable. Only recirculation systems (scenarios 6 and 7) are environmentally sustainable. Another option is to re-use water and nutrients in for example an outdoor cultivation system. The costs of nutrient application are determined by the annual amount of nutrients that are applied to the system, and therefore by the amounts of nutrients taken up by the crop (an inevitable cost that can not be avoided), and drained to the environment (a cost that can be avoided).

It is worth stressing that recirculation has been considered only in scenarios 6 and 7 to limit the number of scenarios. However, technically this option is possible, and presumably also economically feasible, in the other substrate scenarios (2 onwards). Recirculation of drainage water in soilless cultures increases the sustainability of the greenhouse in two ways: 1) enabling a higher water use efficiency, and 2) reducing the environmental impact by avoiding nutrient leaching and pesticide leaching (through lixiviates) to the soil and the groundwater.

The plastic greenhouses are graded less sustainable in terms of construction since the durability of plastic is limited to a maximum of three years. But in areas with frequent strong winds, plastic covers are often blown away by winds and need frequent replacement anyway. Plastic recycling is possible and contributes to reduce the environmental impact of plastic covers. A glass cover has a life time of more than 20 years, and therefore, scores lower on environmental impact in all environmental impact categories than plastic covers in LCA (Torrellas *et al.* 2011).

Pesticide use may reduce both product quality (presence of residues, which can be an important market burden) and product quantity (due to the phytotoxic effects of the chemicals), so avoiding using chemicals is important. A well constructed greenhouse limits the amount of insects that enters, and is therefore an important crop protection measure: it is the first step to limit insect pressure. Furthermore biological control should be applied to control the pests and diseases. The reduced use of chemicals enables the safer use of humble bees for pollination.

Energy use increases if energy is required for heating and for pumps to drive the water recirculation. Mechanical cooling also increases the energy use. The use of energy screens, on the other hand, reduces energy use. Energy use efficiency shows a reverse pattern: it decreases as the technology level increases. The amount of extra produce does not keep pace with the extra amount of energy.

Solar energy increases environmental sustainability (not accounted for in Table 8.).

Table 8. Sustainability factors of the various greenhouse scenarios.

scenario	1	2	3	4	5	6	7
Water use*	o	o	o	o	o	+	++
Nutrient use*	-/o	o	o	o	o	++	++
Construction	o	o	o	o	o	+	+
Pesticides	–	-	o	o	o	o	++
Energy	++	+	-	-	o	o	–

legend: 0 = average// - = worse than average // + = better than average
*: the sustainability of water and nutrient use changes if recirculation is introduced in other scenarios than 6 and 7.

3.9 Economic sustainability

3.9.1 Costs and benefits

Total investment costs increase with the technology level, from 293 Mex. \$ m^{-2} for scenario 1 to 3414 Mex. \$ m^{-2} for scenario 7. A net house in Sinaloa is assumed to require the same investments as a simple greenhouse in Aguascalientes or Querétaro. Taking into account interest rates and depreciation, the annual investment for installation costs range from 65 Mex. \$ $m^{-2} y^{-1}$ to 548 Mex. \$ $m^{-2} y^{-1}$, respectively.

Variable costs vary between 144 Mex. \$ $m^{-2} y^{-1}$ and 564 Mex. \$ $m^{-2} y^{-1}$, respectively, for scenarios 1 and 7 in Aguascalientes; values for Querétaro are very similar. Variable costs for scenario 3 are relatively high because of energy costs. Variable costs for scenario 6 are relatively low because of low energy. Labour costs are assumed constant per m^2 for all scenarios: it is assumed that an increase in technology level also introduces some form of mechanization.

The gross income is the product of the production and the tomato price, and has been assessed on a monthly basis. The difference between gross income and (installation + variable) costs is the net income. The net income is highest for scenarios 6 for Aguascalientes and Querétaro, and scenarios 3-5 for Sinaloa.

The pay-back period is the number of years required to pay back the investments, and after which true profit can be made. The pay-back period is lowest for scenario 1 for Aguascalientes and Querétaro, and for scenario 3 for Sinaloa. This difference is caused by the longer cultivation season and therefore higher income in Sinaloa in an unheated greenhouse. If scenarios 1 and 2 for Aguascalientes and Querétaro are excluded, then the shortest pay-back period is for scenario 6, and 3/4/6, respectively.

More economic details can be found in Annex 5.

Table 9. Summary of economic analysis for Aguascalientes. Results are graphically presented in Annex 4, and more details are given in Annex 5.

Greenhouse character	Dimension	Technology level						
		1	2	3	4	5	6	7
Investment costs	$\$^{+}$ m^{-2}	293	601	1034	1206	1364	1710	3414
Total installation costs****	\$ m^{-2} y^{1}	65	102	156	189	242	264	548
Total variable costs	\$ m^{-2} y^{1}	144	164	582	562	508	289	564
Total income crop	\$ m^{-2} y^{1}	379	489	1037	1045	1045	1110	1440
Net income	\$ m^{-2} y^{1}	171	222	299	292	292	555	324
Pay-back period	year	1.4	2.1	2.6	3.0	3.1	2.4	5.6

Table 10. Summary of economic analysis for Querétaro. Results are graphically presented in Annex 4, and more details are given in Annex 5.

Greenhouse character	Dimension	Technology level						
		1	2	3	4	5	6	7
Investment costs	$\$^{+}$ m^{-2}	293	601	1034	1206	1364	1710	3414
Total installation costs****	\$ m^{-2} y^{1}	65	102	156	189	242	264	548
Total variable costs	\$ m^{-2} y^{1}	142	161	531	470	426	299	632
Total income crop	\$ m^{-2} y^{1}	353	456	1094	1121	1121	1198	1467
Net income	\$ m^{-2} y^{1}	147	192	407	460	451	633	284
Pay-back period	year	1.5	2.4	2.1	2.1	2.3	2.1	5.9

Table 11. Summary of economic analysis for Culiacán . Results are graphically presented in Annex 4, and more details are given in Annex 5.

Greenhouse character	Dimension	Technology level				
		1	2	3	4	5
Investment costs	$\$^{+}$ m^{-2}	293	601	1034	1206	1364
Total installation costs****	\$ m^{-2} y^{-1}	67	104	159	193	248
Total variable costs	\$ m^{-2} y^{-1}	125	145	305	291	213
Total income crop	\$ m^{-2} y^{-1}	213	363	764	776	776
Net income	\$ m^{-2} y^{-1}	21	114	300	290	313
Pay-back period	year	4.4	3.4	2.6	3.0	2.9

Table 12. Summary of economic analysis for Los Sitios. Results are graphically presented in Annex 4, and more details are given in Annex 5.

Greenhouse character	Dimension	Technology level				
		1	2	3	4	5
Investment costs	$\$^{+}$ m^{-2}	293	601	1034	1206	1364
Total installation costs****	\$ m^{-2} y^{-1}	67	104	159	193	248
Total variable costs	\$ m^{-2} y^{-1}	128	149	309	294	248
Total income crop	\$ m^{-2} y^{-1}	256	431	898	914	914
Net income	\$ m^{-2} y^{-1}	61	177	429	425	440
Pay-back period	year	2.8	2.5	2.0	2.2	2.3

+: \$ are Mexican pesos
*: chemicals, substrate, packaging, etc.
**: heating, CO_2, climate control, screening, etc.
***: transport, lifts, packaging area, store, etc.
****: incl. depreciation, maintenance, interest

In economic terms, the pay-back period and the net income (after the pay-back period) are two important considerations in evaluating the economic sustainability of a greenhouse.

In summary, scenario 6 (a glass covered greenhouse with a water re-use installation) requires high investments, but has low variable costs due to a relatively low energy demand, and has therefore a relatively high net income and short pay-back time. The glass cover needs a higher initial investment but it will last for many years resulting in a low depreciation. Re-use of water saves on water and nutrients that also compensates for the higher investment costs.

3.9.2 Price differences

We have used weather and price data of the year 2012. Of course, weather can be different, other events may influence the production, and price levels can change. This will all lead to a different financial yield. We have assessed the sensitivity of the greenhouse production system to such changes, by varying the product price from 70 - 130% of the 2012 values. Results are presented in Figure 35.

The following observations can be made:

- Relatively simple greenhouses in Aguascalientes and Querétaro (scenarios 1and 2) are in terms of pay-back time least sensitive to changes in financial yield;
- A glass-covered greenhouse with a relatively low energy demand and low level of variable costs is also not very sensitive to changes in financial yield;
- The other scenarios show a much greater sensitivity to changes in financial yield, although in the case of Aguascalientes more than in the case of Querétaro;
- The simplest greenhouse in Sinaloa (scenario 1) is most sensitive to changes in financial yield;
- The other greenhouse types in Sinaloa (scenarios 2-5) show a more robust response.

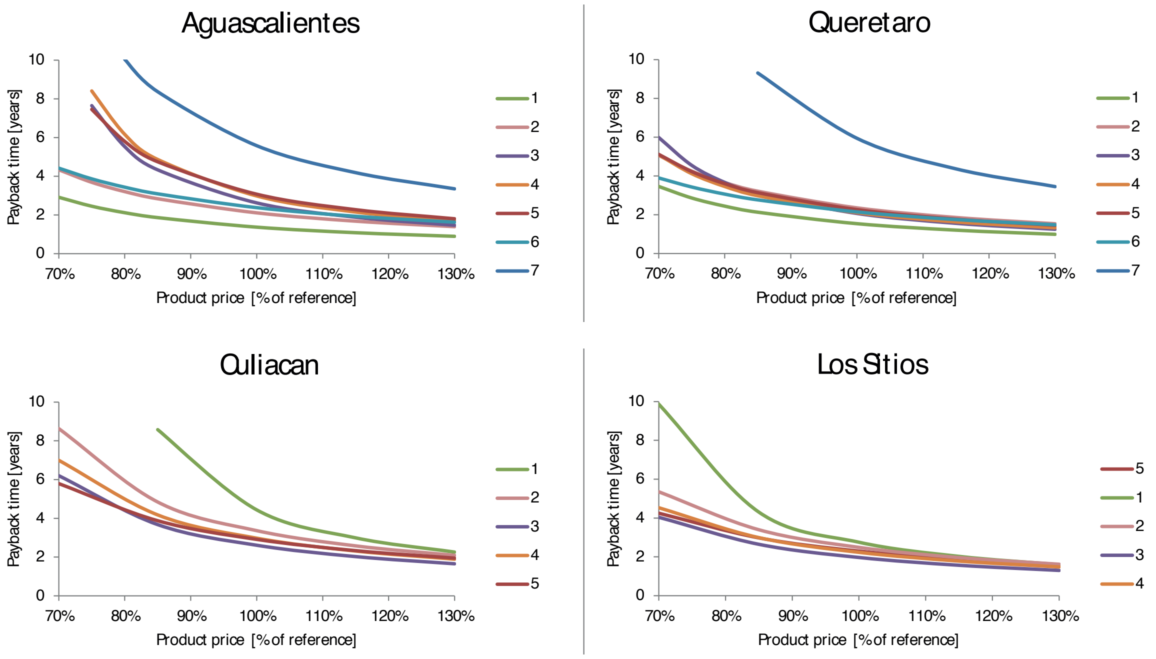

Figure 35. Effects of a relative change in product price (or in product yield) on the pay-back period of the greenhouse.

4 Summary and discussion

There is growing Mexican interest in a transition towards more technological advanced greenhouse systems that produce for the export market. Such transitions must be economically and environmentally viable. This study is a follow-up a study by Elings *et al.* (2013) that quantified for the state of Aguascalientes the consequences in terms of economic and environmental sustainability of transition to more advanced greenhouse systems. This new study expands this assessment to two additional states, viz. Querétaro and Sinaloa.

Climate

The outdoor climate in Aguascalientes and Querétaro is suitable for horticultural production under protected conditions, apart from winter when temperatures are tool low for good crop development and heating is required. The major difference between Aguascalientes and Querétaro is the slightly higher radiation level in Aguascalientes, resulting is higher production levels. In addition, temperatures and relative air humidity in Aguascalientes are slightly higher and lower, respectively, than in Querétaro.

Sinaloa has a substantially warmer outdoor climate than Aguascalientes and Querétaro, enabling year-round tomato production. As the yearly radiation is lower than in Aguascalientes and Querétaro, production levels are lower. The risk of production failure in Sinaloa due to rarely occurring low temperatures can be avoided through installation of screens that reduce night-time heat loss. Screens are more effective than a small heater. Relative air humidity in Sinaloa is higher than in Aguascalientes and Querétaro.

Production levels

In comparison with a nethouse (scenario 1), an un-heated greenhouse with motorized window openings that are controlled by a climate computer (scenario 2) offers better options for climate control. A window fraction of 30% is recommended for all three states. This results in a temperature increase, higher greenhouse transparency (thus more radiation, Figure 36.) and higher production. Scenario 2 also has substrate cultivation, which can be assumed to result in approximately 10% production increase and improved product quality, as substrate cultivation offers better opportunities for crop management.

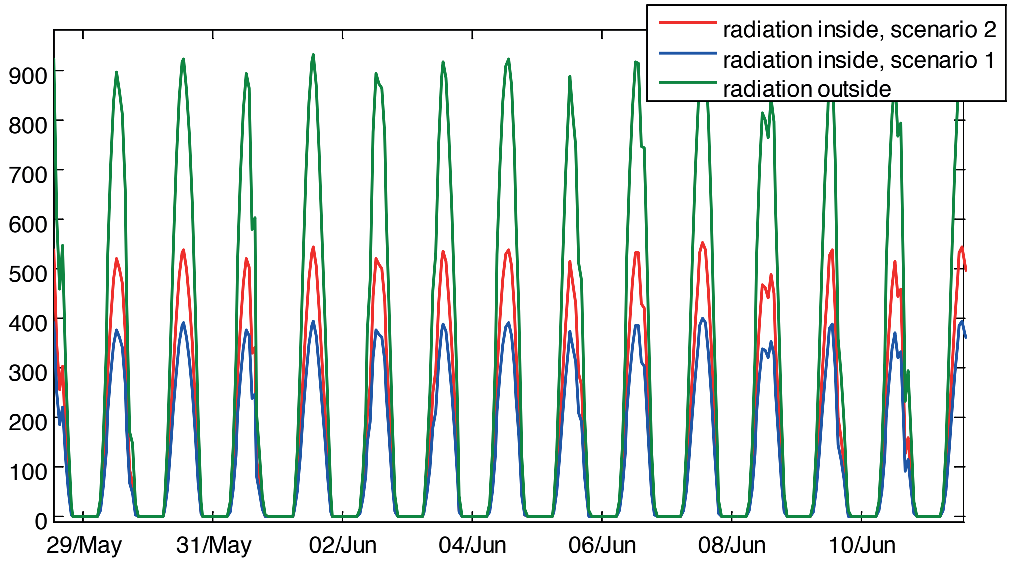

Figure 36. Radiation outside and inside the greenhouse for scenario 1 and 2 in Aguascalientes

Heating (scenario 3) is for the states of Aguascalientes and Querétaro essential to enable year-round cultivation, which is required for an export company. A heating capacity of 100 W m^{-2} is required. For Sinaloa, a heating capacity of 80 W m^{-2} is required. The consequence is of course that the total energy demand rises. To avoid unnecessary costs, an energy screen (scenario 5) can be installed. A heating system also provides CO_2 flue gasses, which considerably improves the production level (Nederhoff, 1994; Qian *et al.* 2012)

Fogging (scenario 4) is a measure to reduce maximum air temperatures through evaporative cooling. Potentially, the cultivation season can be lengthened if summer air temperatures are too high. For the climates in the three states we assessed, this was rarely the case, however, and therefore, the impact on production was limited. It may be possible, however, that the effect is larger in summers that are hotter than we assumed.

We have assessed the effects of an SLS10 Ultra plus screen that is closed at night for (scenario 5). The screen is very effective in avoiding low night-time temperatures, which is relevant for Sinaloa where occasionally low temperatures occur in winter and where greenhouse heating is not available. Closing a shading screen at day-time, increases greenhouse temperature and relative air humidity because of the reduced ventilation rate.

Diffuse glass (scenario 6) has two effects. It realizes a better light spectrum and therefore a better yield. Secondly, it has a better insulation value than plastic because it reflects long-wave heat radiation back into the greenhouse. This results in a lower energy demand in cold periods, but in a larger fogging demand and crop transpiration rate in summer, and therefore a higher water use.

The climate in a semi-closed greenhouse (scenario 7) is controlled as good as possible. The scenario was added for comparative purposes, not because we consider a semi-closed greenhouse as a viable option for Mexico at the moment.

In summary, significant steps in production are realized through using plastic greenhouse cover instead of net greenhouse cover, substrate cultivation, heating + CO_2, glass greenhouse cover, and, for the record, the complete concept of a semi-closed greenhouse. Fogging and screens do not have much impact on production, however, reduce the production risks of high and low temperatures, respectively.

Product quality

Increased technology levels better enable the grower to manage the climate and crop, which normally results in a better product quality and higher product prices. We have not simulated this, and we have neither made assumptions. We have quantified the effect of a higher price, for any reason in paragraph 3.9.2, which may serve as an indication for the consequences of a better (or lower) product quality.

Environmental sustainability: water

Water use depends on the crop transpiration, the amount of drain water, and the amount used by the fogging system. Radiation, temperature and relative air humidity influence crop transpiration; the cultivation system (soil, substrate, recirculation) determine the amount of drain water, and the climate settings determine the water used by the fogging system. The largest steps in water use are made by the introduction of a greenhouse with plastic greenhouse cover and a substrate system, by the introduction of a heating system because the growing season is lengthened, and by a glass greenhouse cover because crop transpiration increases.

Water use efficiency is the amount of water used per kg produced tomatoes. The introduction of recirculation reduces the amount of water used by 13-16% and increases the water use efficiency by 15-17%, depending on the location. Water use and water use efficiency do not vary much among scenarios 3-5; the largest steps are made by scenario 3 (longer growing season) and scenario 7 (semi-closed greenhouse).

Water is scarce in Aguascalientes and Querétaro, and therefore, water use and water use efficiency are important system characters. If the acreage of protected horticulture is going to increase, then water resources are a major consideration. Drain water from a soilless culture system can be used for other purposes, such as outdoor horticulture, further increasing the water use efficiency. A problem, however, is that water is for free. As long as water is not charged, there is no economic incentive for the grower to improve the water use efficiency. As an alternative, certification and associated higher prices or better market positioning (a better water footprint) can stimulate a more responsible use of water.

Environmental sustainability: energy

Energy use increases as the level of technology increases. Energy is needed for heating (scenario 3), pumps to allow water (re-)circulation (scenario 2) and mechanical cooling (scenario 7). Glass cover (scenario 6) has better insulating capacities than plastic cover and therefore reduces the energy needs. Screening (scenario 5) reduces energy needs also because of insulating capacity. Energy use efficiency is relatively high for relatively simple greenhouses: the production is low, but the energy use is even lower. Disregarding scenarios 1, 2 and 7, energy use efficiency is highest for scenario 6, due to the insulating capacities of the glass greenhouse cover.

Fossil energy is expensive, and its usage is not sustainable by default. For Aguascalientes the presence of geothermal energy could be exploited much better. For example in Iceland and Turkey, geothermal energy is being used in greenhouse horticulture. In Hungary, it is by far the cheapest source of energy (Torrellas *et al.* 2011). Technically there should not be a serious limitation. Costs are more difficult to assess at the moment as these are very location specific; more price information would be required.

The capacity to lower high levels of relative air humidity is an important advantage of a heating system. This helps to prevent diseases.

The combustion of gas results in both heat and CO_2, which is, in comparison with other CO_2 options economically most sustainable (we did not assume electricity production). If gas is not available, or if other energy sources are used (geothermal energy, solar energy, biomass), pure CO_2 is a viable option, especially at times of high radiation and the greenhouse closed vents.

Economic sustainability

Investment and fixed costs rise stepwise with increasing level of technology, which requires the purchase of increasingly more hardware. We have assumed that the additional installation costs (transport, packaging area, lifts, store etc.) are 15% of the total installation costs. This amount may vary, depending on the needs of the grower. More investments lead to higher fixed costs, a lower net income and a longer pay-back time.

The use of a heating system (scenario 3) leads to higher variable costs, however, the balance with the increased production and income is such that this has a shorter pay-back time than a greenhouse system without heating (scenario 2).

Product prices are uncertain. We have assumed monthly values that, give an annual average of US$1.39. Assessment of other data sources shows in a wide variation in tomato prices over months, over states and over years. We have assessed the consequences of variation by multiplying the default prices with a certain factor (paragraph 3.9.2.).

The net income is highest for scenarios 6 for Aguascalientes and Querétaro, and scenarios 3-5 for Sinaloa. Scenario 7 has a relatively low net income because of both high fixed and variable costs.

The pay-back period is the number of years required to pay back the investments, and after which true profit can be made. The pay-back period is lowest for scenario 1 for Aguascalientes and Querétaro, and for scenario 3 for Sinaloa. This difference is caused by the longer cultivation season and therefore higher income in Sinaloa in an unheated greenhouse. If scenarios 1 and 2 for Aguascalientes and Querétaro are excluded, then the shortest pay-back period is for scenario 6, and 3/4/6, respectively.

Also scenarios 1 and 2 have a short pay-back time, but are technologically in a different category. Still, the investments needed and the options to generate or lend these funds can be the determining factor. If investment funds are difficult to obtain, scenarios 1 and 2 might be the best option. Net incomes for scenarios 1 and 2 in Sinaloa are very low due to the low production levels (see also García Victoria *et al.* 2011). Improvement in technology, along with better climate control, avoiding *e.g.* low temperatures should result in rising levels of production and product quality.

Summary

In summary, the general trends are that with advancing levels of technology:

- production (kg m^{-2} y^{-1}) increases
- water use (m^3 m^{-2} y^{-1}) increases (with the exception of the highest level of technology, a semi-closed greenhouse)
- energy use (J m^{-2} y^{-1}) increases (with the exception of a greenhouse with a screen and a glass-covered greenhouse)
- sustainability in terms of water (water use efficiency) increases (paragraph 3.5.1)
- sustainability in terms of energy (energy use efficiency) declines (with the exception of a glass-covered greenhouse)

Net income is highest for a glass-covered greenhouse for Aguascalientes and Querétaro, and for systems with heating, CO_2, misting and screens for Sinaloa.

The pay-back period is lowest for scenario 1 for Aguascalientes and Querétaro, and for scenario 3 for Sinaloa. If the most simple and closed greenhouse for Aguascalientes and Querétaro are excluded (because they are very different technological levels), then pay-back periods for the remaining scenarios do not differ very much.

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Annex I Model descriptions

KASPRO greenhouse model

KASPRO is an extensive dynamic simulation model that simulates a full-scale virtual greenhouse based on the greenhouse construction elements, ventilation openings, greenhouse equipment, different covering materials and their properties (transmission, reflection, and emission), set points for inside climate and the outside climate of a given location. Any computed physical quantity can be listed as output, but for the current project the observed output comprises the realised greenhouse climate at every hour of the year, the energy consumption, the amount of water evaporated by the crop, the amount of CO_2 applied and the dry matter production of the crop.

The model is based on the computation of relevant heat and mass balances (Bot, 1983). The heat balances describe both the convective and irradiative processes. The mass balances are constituted from exchange processes through leakage and ventilation (de Jong, 1990). They include canopy transpiration (Stanghellini, 1987) and condensation at cold surfaces. The mass balances around the CO_2-concentration are based on losses of CO_2 by ventilation and photosynthesis, and gains of CO_2 by dosing and respiration.

Basically, the model describes the entrance of solar radiation into a greenhouse structure and computes the heat and moisture fluxes induced from this radiation. The heat and moisture is released predominantly by the canopy, but the heat fluxes originate from other opaque elements in the envelope as well. Also, reflection of solar radiation, typically by the covering structure and by reflecting shading screens, is taken into account. The heat and moisture fluxes affect the air conditions around the canopy, which are in dynamic interaction with the greenhouse construction and the environment. To a certain extent, the interaction between the microclimate around the canopy and the environment can be controlled by means of heating, ventilation, humidification and dehumidification, CO_2 application, shading and optionally even by means of cooling.

Greenhouse climate is controlled by a replica of commercially available climate controllers. The total set of differential equations is solved numerically (de Zwart, 1996). The control actions coming from the greenhouse climate controller are an integral part of the simulation model. According to user defined settings for the inside climate conditions that are to be achieved the controller increases or decreases the heating power, opens or closes the ventilation openings, applies fogging and CO_2 enrichment, opens or closes screening tissues and turns on cooling system.

For this project, the KASPRO simulation model was used to analyse the effect of local outside climate conditions on inside greenhouse climate and crop response with an assumed greenhouse configuration. The effect of cooling by natural ventilation or evaporative cooling by fogging and mechanical cooling was analysed.

The result of all KASPRO simulations were the realised greenhouse climate at every hour of the year, the energy consumption, the amount of water transpired by the crop, the amount of CO_2 applied and the dry matter production of the crop for different scenario's. These results were then used to feed the economic model.

Assumptions for the Kaspro model

- Greenhouse size: 1 ha;
- Heating system (scenario 3 and higher) consists of a lower heating net of 5 pipes of 51mm diameter and a higher heating net of 2.5 pipes of 28mm per 4 meter. Heat is generated with a boiler, in compination with a heat buffer of 100m^3 per ha. The boiler has a condenser;
- The low tech greenhouse (sceneario 1) has a 20% lower light transmissivity than the plastic greenhouse from the other scenarios. The effect of ageing of the plastic film is not taken into account, as well as the fact that a glass roof may be cleaned more easilly;
- Humidity control is applied when the humidity is above 80% in the greenhouse;
- The characterics of a normal thermal screen are used. The screen is closed when the light level drops below 50W/m^2 and the outside temperature is less than 12 °C;
- Properties of the plastic roof cover are:
  - diffuse transmission 75%;
  - direct light transmission 83%;
  - IR transmission: 39%.
- Properties of the plastic roof cover are:
  - diffuse transmission 76%;
  - direct light transmission 84%;
  - IR transmission: 0%.
- Properties of the energy screen
  - direct light transmission 88%;
  - diffuse transmission 81%;
  - IR transmission: 47%.
  - screen is air tight (apart from air leakage).

INTKAM crop model

The Intkam model simulates growth and development of a number of greenhouse crops, amongst others of tomato. Crop photosynthesis rate is computed at small time steps (5-60 min) with a biochemical model (Farquhar *et al.* 1980; Goudriaan, 1986) on the basis of radiation, CO$_2$, temperature and relative air humidity. Instantaneous rates are integrated to a daily crop photosynthesis rate. Daily dry matter partitioning and organ growth rates based on the sink strengths of various organs and assimilate availability (Marcelis *et al.* 2006). Crop transpiration rate is simulated in a similar manner. Intkam simulates the number of trusses (and fruits) on a daily basis, and the daily weight of harvested fruits. These processes also depend on the environmental conditions.

Financial model

In the economic model several scenarios concerning different degrees of technology are analyzed to find the optimum greenhouse design. The economic model is based on the systematic calculation method given by KWIN (2010). Benefits and costs are calculated on an annual basis. On one side the yield and product price are calculated as benefits, on the other side costs of heat and electricity, plant material, labour costs, costs for crop protection, crop nutrition, water, substrate, plastic films, wires, clips and packaging with related cost prices are calculated as variable costs. Next to that the initial investments for installations like greenhouse construction, covering material, screening, insect netting, heating and cropping system, irrigation system, CO$_2$ dosing, fogging, climate control and general costs for supervision, transport, packaging area and machinery are calculated per scenario. Initial investments are calculated back to annual costs by taking into account depreciation, maintenance and interest. The balance of benefits and total costs results in the net result. Besides, the payback period is calculated by the total investment sum divided by the cash flow (net profit + depreciations) . After all a sensitivity analysis is done with which the effect of variations of product price and investments is calculated on the payback period.

Several input data for the cost-benefit analysis are given by the model calculations. The virtual greenhouse model KASPRO gives data on heat, electricity, CO_2 and water consumption, and the INTKAM model provides crop yield data, which are used as input data for the economic model. The amount of plant material is assumed to be 2 plants per m^2. The costs for crop protection, crop nutrition, substrate, plastic film, wires and clips are taken from KWIN (2010) and are adapted to the Mexican situation based on interviews and data delivered by professionals (see paragraph 1.3). For all scenarios labour costs are assumed to vary in proportion to the yield. It is not considered that the labour costs are higher in the traditional Mexican greenhouses due more manual work instead of the use of machinery. An open irrigation system is assumed to consume 20% more water than a closed irrigation system. The costs for packaging are assumed to vary with yield. Prices for energy and electricity and labour are given by local information. Depreciation is assumed to be 3 years for plastic film covering material, insect netting, screening and CO_2 system. For most other installations it is assumed to be 15 years. Maintenance costs are between 2% and 8%, depending on the equipment (KWIN, 2010). The seasonal tomato producers prices were given by. For all economic calculations a company size of minimum 2 ha is assumed. The total investment of the company is taken into account incl. general facilities and packaging area. An overview of assumptions of prices, depreciation, maintenance and resulting annual costs of investments are given in Annex 1 and 2.

Annex II Assumptions for the economic analysis

Table 13. Summary of variable costs for resources.

Item	**Price (MX $)**	source of information
natural gas [price/m3]	$ 12.07	La Huerta
electricity [price/kWh]	$ 0.38	La Huerta
CO_2 [price/kg] pure	$ 3.43	not known
plant material [price/plant]	$ 16.47	La Huerta
labour costs crop [price/h]**	$ 38.10	La Huerta
crop protection [price/m2]	$ 17.16	La Huerta
crop nutrition closed cycle [price/kg tomatoes]	$ 0.96	KWIN*
water [price/m3] (water system, irrigation, fogging)	$ 0.67	La Huerta
substrate	$ 22.31	KWIN*
plastic film, wires, clips	$ 8.58	KWIN*
packaging /sorting etc.	$ -	to be determined
rent for land [price/m3]	$ 7.34	Not included

*KWIN: Vermeulen, 2010.
** It has been assumed that 1 m^2 of tomato greenhouse requires 1 hour of labour on an anual basis (KWIN 2010 uses a value of 0.93 h m^{-2} y^{-1} for a high-tech Netherlands greenhouse).

Table 14. Product prices. The domestic and export prices have been provided by Huerta for 2010 and 2011 together with their production ratio over the production period for domestic and export. Based on this information tomato prices for every month have been calculated.

Price 1 kg of tomato in mex. $	**Domestic and export price combined**	**Export price**
January	21,760	24,960
February	17,536	22,144
March	13,440	14,848
April	10,240	10,880
May (assumed)	10,240	6,400
June (assumed)	10,240	6,400
July (assumed)	10,240	6,400
August (assumed)	10,240	6,400
September	11,648	20,992
October	12,032	13,568
November	13,696	15,744
December	17,152	19,456

Tabel 15. Investment costs per m^2 *greenhouse ground area.*

Item	Overall investment $\text{Mex \$ m}^{-2}$	depreciation [% year^{-1}]	maintenance [% year^{-1}]	interest rate [%/ year]	Yearly costs $\text{Mex \$ m}^{-2}$	source of infor-mation
modern glass greenhouse incl. covering (1 ha)	574.86	7	0.5	4	66.11	KWIN
glass covering (diffuse, extra)	68.64	7	0.5	4	7.89	Industry
double glazing	205.92	7	0.5	4	23.68	Industry
modern plastic film greenhouse (excl. covering)	308.88	7	2	4	40.15	KWIN
plastic film covering	25.74	30	5	4	10.04	KWIN
Traditional plastic film greenhouse	171.60	15	2	4	36.04	KWIN
Net greenhouses	145.86	15	2	4	30.63	KWIN
Net	34.32	30	5	4	13.38	KWIN
Concrete paths (5% greenhouse area)	21.45	7	1	4	2.57	KWIN
Concrete floor	669.24	7	1	4	80.31	KWIN
Heating system in the greenhouse	108.97	7	0.5	4	12.53	KWIN
Growing pipe in the greenhouse	41.18	7	0.5	4	4.74	KWIN
heating system (boiler) 100 W/m^2, 1 ha	102.96	7	1	4	12.36	KWIN
air heating unit (13 m^3/hour), 1 per 100 m^2	17.16	15	2.5	4	3.69	KWIN
heat storage, 120 m^3	109.82	7	2	4	14.28	KWIN
Piping	34.32	7	0.5	4	3.95	KWIN
Cooling system (heat pump) 500 W/m^2, 1 ha	1,201.20	7	2	4	156.16	KWIN
Cooler in the greenhouse every 50 m^2	686.40	7	2	4	89.23	KWIN
screening system	137.28	25	5	4	46.68	KWIN
insect netting	128.70	20	2	4	33.46	KWIN
CO_2 dosing (1ha) + detection	14.93	10	5	4	2.84	KWIN
fogging system	85.80	10	5	4	16.30	KWIN
CO_2 from boiler installation	5.58	10	5	4	1.06	KWIN
dehumidification system (outside air)	317.46	10	5	4	60.32	KWIN
Pad and Fan system (35 m)	429.00	15	5	4	102.96	assumption
Fertigation system A B container and drippers	48.91	15	5	4	11.74	KWIN
Water storage tanks	17.16	15	5	4	4.12	KWIN
re-circulation and desinfection	60.06	7	2	4	7.81	KWIN
RO installation (50 m^3/day)	48.91	7	2	4	6.36	KWIN
artificial lighting (60W/m)	600.60	15	1	4	120.12	KWIN
climate computer simple	17.16	15	8	4	4.63	KWIN
climate computer advanced	60.06	15	8	4	16.22	KWIN
Building (computer, canteen, storage, packaging etc.) 10% of greenhouse	892.32*	7	0.5	4	102.62	KWIN
Storage (cooled) 1% greenhouse area	1,544.40	7	1	4	185.33	KWIN
Gutters (m^{-2})	120.12	12.5	1	4	21.02	KWIN

*: for the costs of additional buidlings, 10% of the value of other greenhouse costs is assumed.

Annex III Scenario results for Aguascalientes and Querétaro

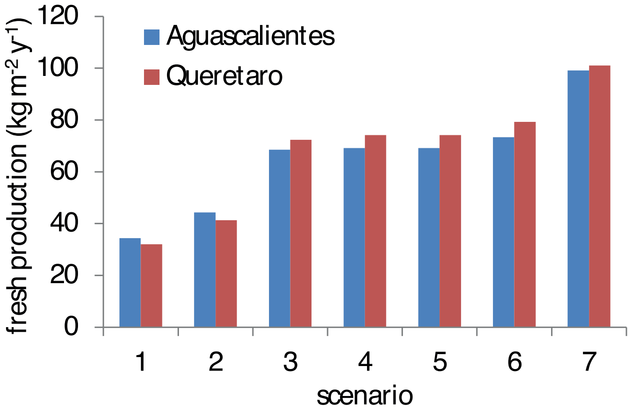

Figure 37. Annual fresh tomato production for the various scenarios (values are computed).

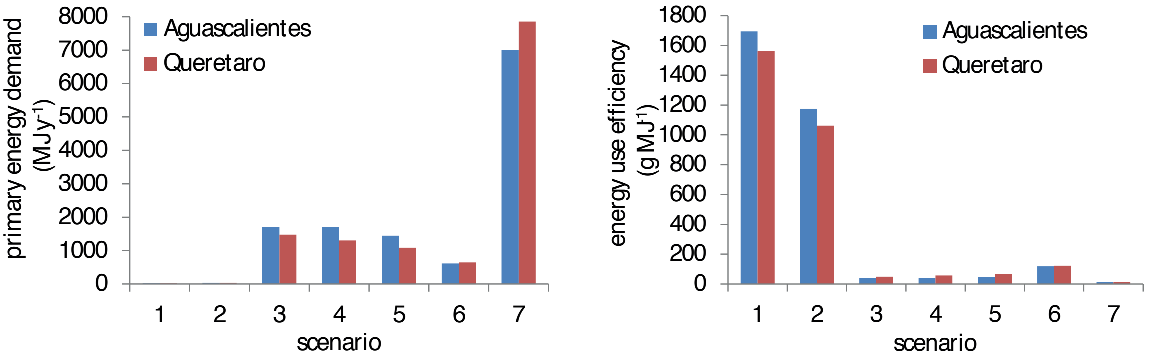

Figure 38. Annual energy use and energy use efficiency for the various scenarios (values are computed).

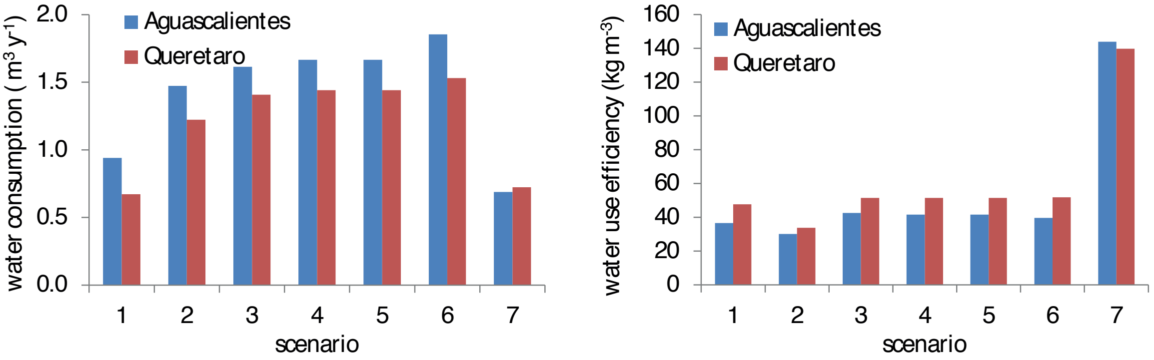

Figure 39. Annual water use and water use efficiency for the various scenarios (values are computed).

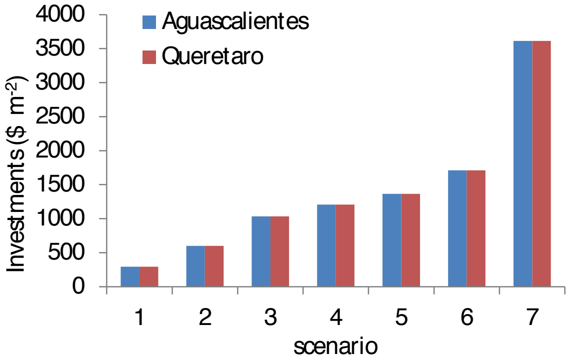

Figure 40. Total investments for greenhouse construction and installation for the various scenarios (values are computed).

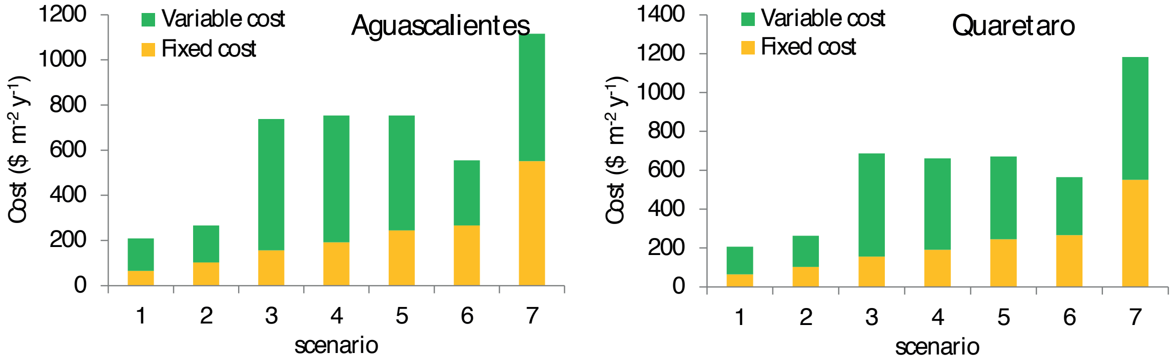

Figure 41. Annual variable and fixed costs for the various scenarios (values are computed).

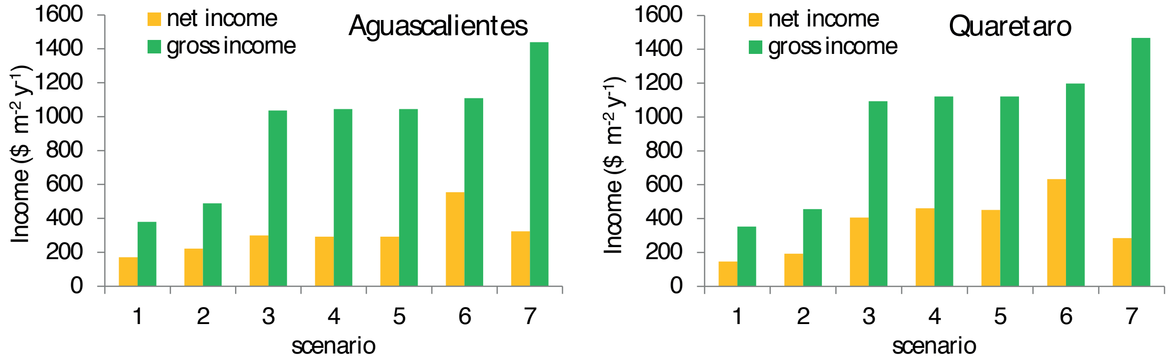

Figure 42. Annual gross and net income for the various scenarios (values are computed).

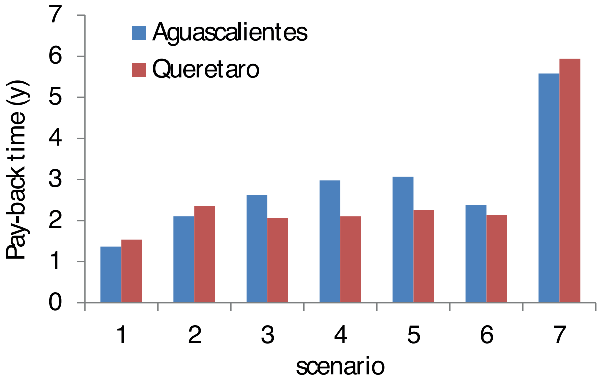

Figure 43. Pay-back time for the various scenarios (values are computed).

Annex IV Scenario results for Sinaloa

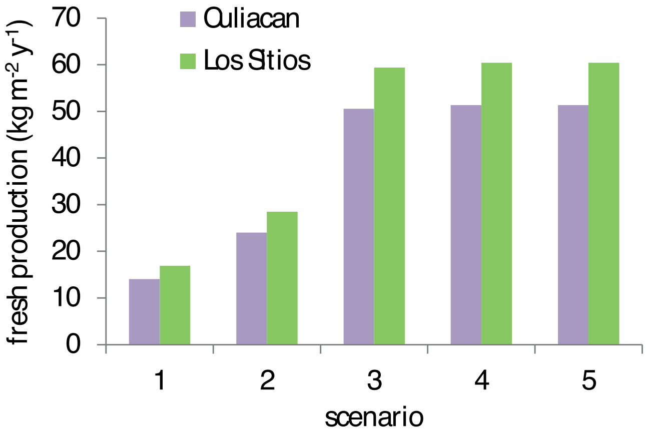

Figure 44. Annual fresh tomato production for the various scenarios (values are computed).

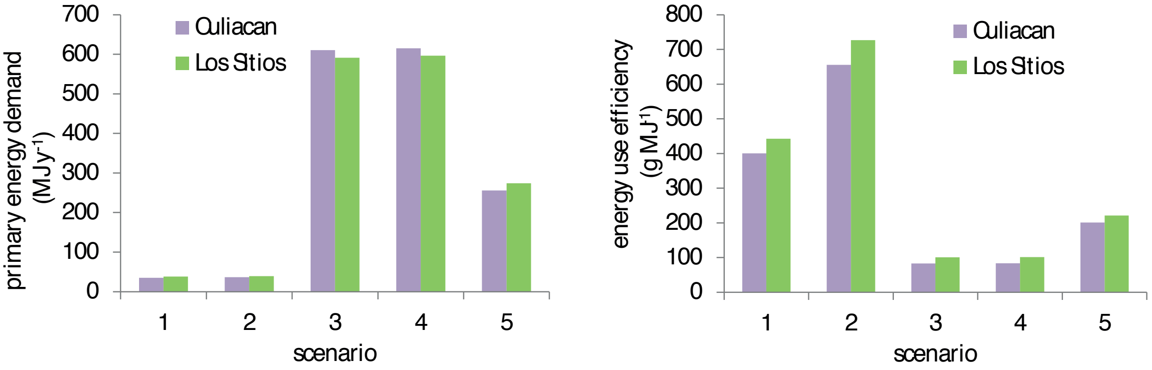

Figure 45. Annual energy use and energy use efficiency for the various scenarios (values are computed).

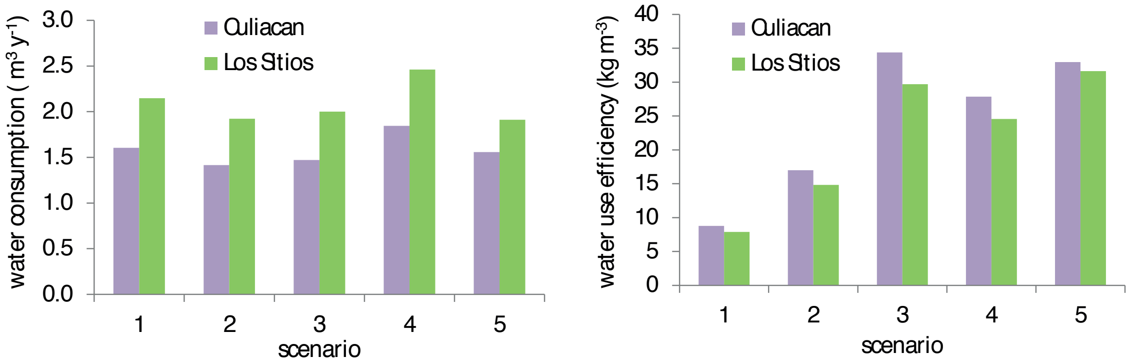

Figure 46. Annual water use and water use efficiency for the various scenarios (values are computed).

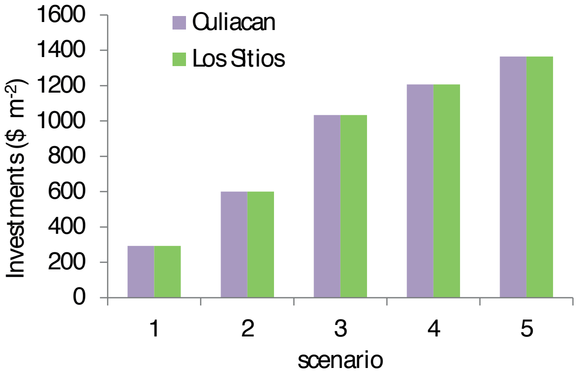

Figure 47. Total investments for greenhouse construction and installation for the various scenarios (values are computed).

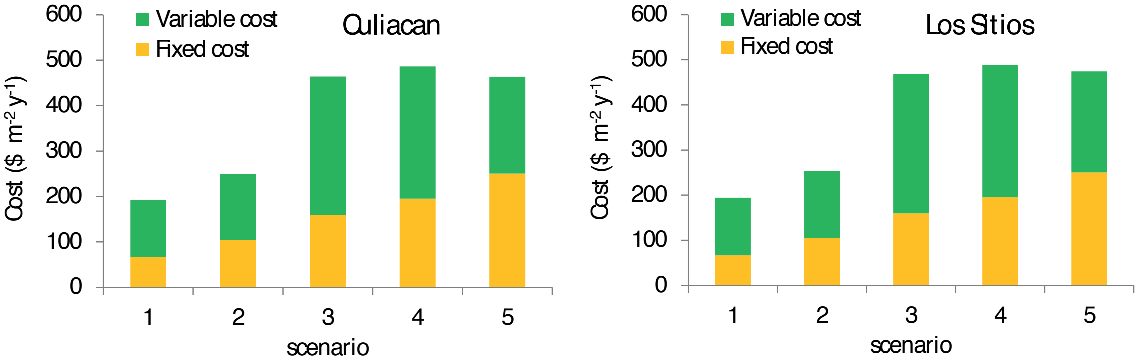

Figure 48. Annual variable and fixed costs for the various scenarios (values are computed).

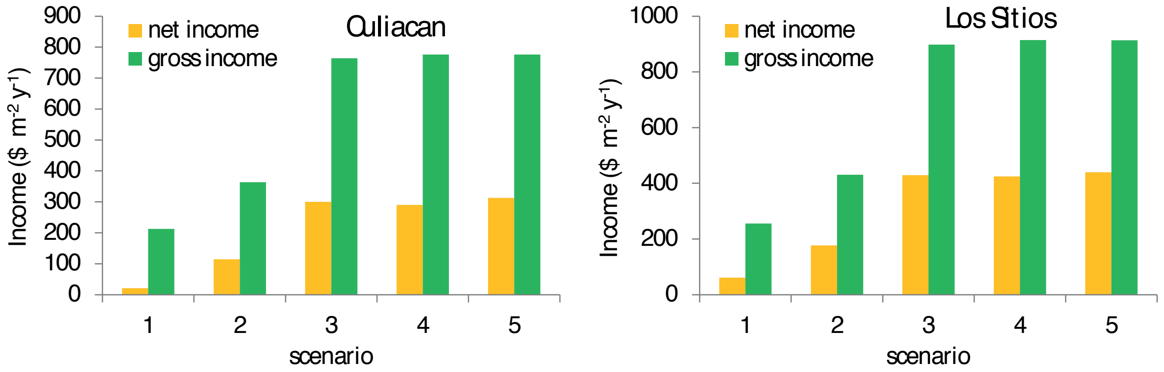

Figure 49. Annual gross and net income for the various scenarios (values are computed).

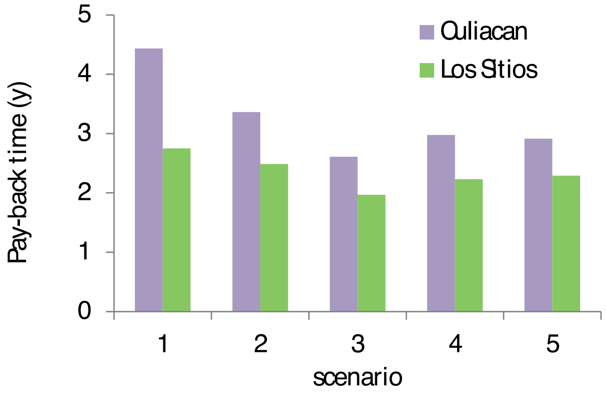

Figure 50. Pay-back time for the various scenarios (values are computed).

Annex V Economic overviews

Table 16. Summary of economic analysis for Aguascalientes.

Greenhouse character	Dimension	Technology level						
		1	2	3	4	5	6	7
Investment costs	**$\$^{+}\ m^{-2}$**	**293**	**601**	**1034**	**1206**	**1364**	**1710**	**3614**
Greenhouse construction and covering	$\$\ m^{-2}\ y^{-1}$	36	50	50	50	50	66	74
Other installation costs**	$\$\ m^{-2}\ y^{-1}$	20	20	67	95	142	144	384
Additional installation costs***	$\$\ m^{-2}\ y^{-1}$	8	32	39	43	50	53	90
Total installation costs****	**$\$\ m^{-2}\ y^{-1}$**	**65**	**102**	**156**	**189**	**242**	**264**	**548**
Energy and CO_2	$\$\ m^{-2}\ y^{-1}$	1	2	396	396	334	137	389
Labour	$\$\ m^{-2}\ y^{-1}$	38	38	38	38	38	38	38
Water, nutrients and recirculation	$\$\ m^{-2}\ y^{-1}$	35	44	67	51	51	36	48
Others*	$\$\ m^{-2}\ y^{-1}$	70	81	81	78	86	78	89
Total variable costs	**$\$\ m^{-2}\ y^{-1}$**	**144**	**164**	**582**	**562**	**508**	**289**	**564**
Total income crop	**$\$\ m^{-2}\ y^{-1}$**	**379**	**489**	**1037**	**1045**	**1045**	**1110**	**1440**
Net income	**$\$\ m^{-2}\ y^{-1}$**	**171**	**222**	**299**	**292**	**292**	**555**	**324**
Pay-back period	**year**	**1.4**	**2.1**	**2.6**	**3.0**	**3.1**	**2.4**	**5.6**

+: $ are Mexican pesos
*: chemicals, substrate, packaging, etc.
**: heating, CO_2, climate control, screening, etc.
***: transport, lifts, packaging area, store, etc
****: incl. depreciation, maintenance, interest

Table 17. Summary of economic analysis for Querétaro.

Greenhouse character	Dimension	Technology level						
		1	2	3	4	5	6	7
Investment costs	**$\$^{+}\ m^{-2}$**	**293**	**601**	**1034**	**1206**	**1364**	**1710**	**3614**
Greenhouse construction and covering	$\$\ m^{-2}\ y^{-1}$	36	50	50	50	50	66	74
Other installation costs**	$\$\ m^{-2}\ y^{-1}$	20	20	67	95	142	144	384
Additional installation costs***	$\$\ m^{-2}\ y^{-1}$	8	32	39	43	50	453	90
Total installation costs****	**$\$\ m^{-2}\ y^{-1}$**	**65**	**102**	**156**	**189**	**242**	**264**	**548**
Energy and CO_2	$\$\ m^{-2}\ y^{-1}$	1	2	341	300	247	144	456
Labour	$\$\ m^{-2}\ y^{-1}$	38	38	38	38	38	38	38
Water, nutrients and recirculation	$\$\ m^{-2}\ y^{-1}$	33	41	70	54	54	39	49
Others*	$\$\ m^{-2}\ y^{-1}$	70	81	81	78	86	78	89
Total variable costs	**$\$\ m^{-2}\ y^{-1}$**	**142**	**161**	**531**	**470**	**426**	**299**	**632**
Total income crop	**$\$\ m^{-2}\ y^{-1}$**	**353**	**456**	**1094**	**1121**	**1121**	**1198**	**1467**
Net income	**$\$\ m^{-2}\ y^{-1}$**	**147**	**192**	**407**	**460**	**451**	**633**	**284**
Pay-back period	**year**	**1.5**	**2.4**	**2.1**	**2.1**	**2.3**	**2.1**	**5.9**

+: \$ are Mexican pesos
*: chemicals, substrate, packaging, etc.
**: heating, CO_2, climate control, screening, etc.
***: transport, lifts, packaging area, store, etc
****: incl. depreciation, maintenance, interest

Table 18. Summary of economic analysis for Culiacán .

Greenhouse character	Dimension	Technology level				
		1	2	3	4	5
Investment costs	**$\$^{+}\ m^{-2}$**	**293**	**601**	**1034**	**1206**	**1364**
Greenhouse construction and covering	$\$\ m^{-2}\ y^{-1}$	36	50	50	50	50
Other installation costs**	$\$\ m^{-2}\ y^{-1}$	20	20	67	95	142
Additional installation costs***	$\$\ m^{-2}\ y^{-1}$	10	33	42	47	55
Total installation costs****	**$\$\ m^{-2}\ y^{-1}$**	**67**	**104**	**159**	**193**	**248**
Energy and CO_2	$\$\ m^{-2}\ y^{-1}$	2	2	136	137	52
Labour	$\$\ m^{-2}\ y^{-1}$	38	38	38	38	38
Water, nutrients and recirculation	$\$\ m^{-2}\ y^{-1}$	16	24	50	38	38
Others*	$\$\ m^{-2}\ y^{-1}$	70	81	81	78	86
Total variable costs	**$\$\ m^{-2}\ y^{-1}$**	**125**	**145**	**305**	**291**	**213**
Total income crop	**$\$\ m^{-2}\ y^{-1}$**	**213**	**363**	**764**	**776**	**776**
Net income	**$\$\ m^{-2}\ y^{-1}$**	**21**	**114**	**300**	**290**	**313**
Pay-back period	**year**	**4.4**	**3.4**	**2.6**	**3.0**	**2.9**

+: $\$$ are Mexican pesos
*: chemicals, substrate, packaging, etc.
**: heating, CO_2, climate control, screening, etc.
***: transport, lifts, packaging area, store, etc
****: incl. depreciation, maintenance, interest

Table 19. Summary of economic analysis for Los Sitios.

Greenhouse character	Dimension	Technology level				
		1	2	3	4	5
Investment costs	**$\$^{+}\ m^{-2}$**	**293**	**601**	**1034**	**1206**	**1364**
Greenhouse construction and covering	$\$\ m^{-2}\ y^{-1}$	36	50	50	50	50
Other installation costs**	$\$\ m^{-2}\ y^{-1}$	20	20	67	95	142
Additional installation costs***	$\$\ m^{-2}\ y^{-1}$	10	33	42	47	55
Total installation costs****	**$\$\ m^{-2}\ y^{-1}$**	**67**	**104**	**159**	**193**	**248**
Energy and CO_2	$\$\ m^{-2}\ y^{-1}$	2	2	132	133	55
Labour	$\$\ m^{-2}\ y^{-1}$	38	38	38	38	38
Water, nutrients and recirculation	$\$\ m^{-2}\ y^{-1}$	18	29	58	45	45
Others*	$\$\ m^{-2}\ y^{-1}$	70	81	81	78	86
Total variable costs	**$\$\ m^{-2}\ y^{-1}$**	**128**	**149**	**309**	**294**	**248**
Total income crop	**$\$\ m^{-2}\ y^{-1}$**	**256**	**431**	**898**	**914**	**914**
Net income	**$\$\ m^{-2}\ y^{-1}$**	**61**	**177**	**429**	**425**	**440**
Pay-back period	**year**	**2.8**	**2.5**	**2.0**	**2.2**	**2.3**

+: $ are Mexican pesos
*: chemicals, substrate, packaging, etc.
**: heating, CO_2, climate control, screening, etc.
***: transport, lifts, packaging area, store, etc
****: incl. depreciation, maintenance, interest

Wageningen UR Greenhouse Horticulture

Adres : Droevendaalsesteeg 1, 6708 PB Wageningen
: Postbus 644, 6700 AP Wageningen
Tel. : 0317 - 48 60 01
Fax : 0317 - 41 80 94
E-mail : glastuinbouw@wur.nl
Internet : www.glastuinbouw.wur.nl

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