Supplementary Material

# Life Cycle Inventory Data

Table S1 provides information on the life cycle inventory data employed in the baseline and current scenarios. Other LCI datasets employed for the past and future scenarios and sensitivity analyses are included in the corresponding sections below.

*Table S1: Life Cycle Inventory (LCI) data employed in the Baseline and Current Scenarios (Other LCI data employed in past and future scenarios are outlined in sections below). All datasets from Ecoinvent v 3.7*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Type | Category | Specific Category | Product/System | LCI dataset |
| Inputs | ***Material Inputs*** | **Growing Medium** | Peat | market for peat moss | peat moss | Cutoff, S |
| Perlite | market for expanded perlite | expanded perlite | Cutoff, S |
| Wood Chips | market for wood chips, wet, measured as dry mass | wood chips, wet, measured as dry mass | Cutoff, Sv |
| Sand | market for sand | sand | Cutoff, S |
| Horn Meal | market for horn meal | horn meal | Cutoff, S |
| **Organic Fertilizers** | Food Industry By-Products | *No information included due to proprietary reasons* |
| **Seeds** | Seeds | grass seed production, organic, for sowing | grass seed, organic, for sowing | Cutoff, S |
| **Water** | Tap Water | market for tap water | tap water | Cutoff, S |
| Rain Water | market for water, harvested from rainwater | water, harvested from rainwater | Cutoff, S |
| **Other** | CO2 (enrichment) | market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, S |
| **Packaging/Pots** | Polystyrene (PS) | polystyrene production, general purpose | polystyrene, general purpose | Cutoff, S |
| Recycled Polypropylene (PP) | polypropylene production, granulate | polypropylene, granulate | Cutoff, S |
| Polypropylene | polypropylene production, granulate | polypropylene, granulate | Cutoff, S |
| LLDEPE | market for packaging film, low density polyethylene | packaging film, low density polyethylene | Cutoff, S |
| Polyethylene | polyethylene production, high density, granulate |
| Polyethylene (Recycled) | polyethylene terephthalate production, granulate, amorphous, recycled | polyethylene terephthalate, granulate, amorphous, recycled | Cutoff, S |
| PET | polyethylene terephthalate production, granulate, amorphous | polyethylene terephthalate, granulate, amorphous | Cutoff, S |
| Cardboard | market for corrugated board box | corrugated board box | Cutoff, S |
| **Energy Inputs** | Electricity | market for electricity, medium voltage | electricity, medium voltage, SE | Cutoff, S |
| Nordic Mix | NordEL-electricity, high voltage, production mix | electricity, high voltage  |
| Hydropower | electricity production, hydro, reservoir, non-alpine region | electricity, high voltage  |
| Wind  | electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage |
| Pellets | market for wood pellet | wood pellet, measured as dry mass | Cutoff, S (5kg/kwh) |
| **Cultivation and Packaging Waste Handling** | Plastic Waste(Incineration) | treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | Cutoff, S |
| Plastic Waste (Recycling) | treatment of waste polyethylene, for recycling, unsorted, sorting | waste polyethylene, for recycling, sorted | Cutoff, S |
| Organic/Bio-Based Waste | treatment of biowaste, industrial composting | biowaste | Cutoff, S |
| General Wastes | treatment of municipal solid waste, incineration | municipal solid waste | Cutoff, S |
| Cardboard/Paper Waste | treatment of waste paper, unsorted, sorting | waste paper, sorted | Cutoff, S |
| Infrastructure | **Infra.** | Greenhouse Structure | market for greenhouse, glass walls and roof | greenhouse, glass walls and roof | Cutoff, S |
| Other Buildings | market for building, hall, steel construction | building, hall, steel construction | Cutoff, S |
| Pellets Furnace | market for furnace, pellets, with silo, 300kW | furnace, pellets, with silo, 300kW | Cutoff, S |
| HPS Light Fixtures | *See info in section on lighting below* |
| LED | *See info in section on lighting below* |
| Tanks |  |
| Pumps | pump production, 40W | pump, 40W | Cutoff, S |
| Piping | polyethylene pipe production, DN 200, SDR 41 | polyethylene pipe, DN 200, SDR 41 | Cutoff, S |
| Other Equipment (Bagging/Conveyors) | market for electronic component, passive, unspecified | electronic component, passive, unspecified | Cutoff, S |
| Transportation | Truck | market for transport, freight, lorry 28 metric ton, vegetable oil methyl ester 100% | transport, freight, lorry 28 metric ton, vegetable oil methyl ester 100% | Cutoff, S |
| Car | transport, passenger car, electric | transport, passenger car, electric | Cutoff, S |

# Scenario Assumptions

Table S2 provides an account of changes made to the scenarios longitudinally, starting with the Original (2014) scenario. See descriptions below, and in the main text, for further information about the changes.

*Table S2: Overview of changes made in the different scenarios compared to the corresponding previous scenarios*

|  |  |
| --- | --- |
| Past/Current Scenarios | Change made compared to Previous Scenario |
| Organic Fertilizer (2016) | * Conventional Fertilizers Replaced with Organic Fertilizers
* Additional infrastructure for nitrification processes
 |
| Pellet Burner (2018) | * Bio-oil burner changed to pellet burner
 |
| Baseline (2019) | * Reduction in share of fossil fuels in transportation (inclusion of more biofuels). Previous scenarios assumed to have only 10% biofuels, while Baseline scenario has assumed 62% biofuels.
 |
| Current Scenario (2021) | * Black PS pots and trays changed to green-recycled PP pots and trays
* Reduced weight in plastics
 |
| Future Scenarios | **Change made compared to Current Scenario** |
| Future-Sustainable Plastic | * Change from PP to recycled PE sleeves
* Increased weight of packaging/increased transportation
 |
| Future-Densify | * Increase from roughly 20 to 30 million pots
* Increase in resource consumption for plants
* Increase in transportation logistics
 |
| Future-Biofuel Transport | * Increase to 90% biofuels in logistics transportation
 |
| Future-LED Lighting | * Switch to LED lighting, including infrastructure
* Reduction of electricity demand
* Increase in heat demand
 |

## Greenhouse Infrastructure

The greenhouse size and information about the structure was provided based on information from Svegro and a study visit to learn more about their production system. For the infrastructure requirements, including the greenhouse structure and supporting infrastructure for the hydroponic NFT system, the Ecoinvent dataset ‘market for greenhouse, glass walls and roof | Cutoff, S,’ was employed and was assumed to cover the greenhouse infrastructure. This was done as no changes in the greenhouse infrastructure were modeled in the studied scenarios, and as such, we made the assumption upon reviewing the dataset that it would be adequate for modeling the greenhouse structure.

We employed the overall size of the growing area to model the greenhouse, i.e., 44 200 m2. HPS lighting was included separately, in addition to the added tanks and the pellet furnace for thermal energy. It was assumed that all the channels for the hydroponic NFT system were included in the greenhouse LCI dataset as mentioned above. This was due to the fact that the dataset includes an extensive listing of different infrastructure, including tubing for fertigation systems. The assumed lifetime for the greenhouse was 30 years. Other structures used for storage and offices (roughly 10 000 m2) were also included and modeled with the dataset ‘market for building, hall, steel construction | Cutoff, S.’ Other infrastructure included in the study has been outlined in respective sections in this Supplementary material and a listing of LCI datasets are provided in Table S1 for further details.

## Packaging in the Baseline, Current and Future Scenarios

For the different scenarios, packaging varies. All past scenarios, including the baseline scenario, were assumed to have the same packaging amounts (and types of plastic) as those outlined in the baseline scenario. As outlined in the main text, the current scenario contains a change in the amount and type of plastic used for the pots and outer wrapping sleeve of the plant. Finally, for the Future-Sustainable Plastic scenario, additional changes in the amounts and types of plastics, as outlined in the main text, are also included. Figures for the amounts and details on the types of plastics employed for the Baseline, Current, and Future-Sustainable Plastic scenarios are included in Table S3 below.

*Table S3: Packaging Amounts and Types in the Baseline and Current scenarios*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Scenario** | **Type** | **Amount** | **Unit** | **Note** |
| Baseline | Polystyrene (PS) | 1 672 | kg |  |
| Pots (PS) | 90 101 | kg | Black |
| Trays (PS) | 93 513 | kg | Black |
| Sleeves, Polypropylene (PP) | 91 181 | kg |  |
| Wrapping (LLDEPE) | 2 191 | kg |  |
| Other (PET) | 367 | kg |  |
| Cardboard | 525 190 | kg |  |
| Current | PS | 1 672 | kg |  |
| Pots (PP) | 65 091 | kg | Green Recycled |
| Trays (PP) | 57 795 | kg | Green Recycled |
| Sleeves (PP) | 91 181 | kg |  |
| Wrapping (LLDEPE) | 2 191 | kg |  |
| Other (PET) | 367 | kg |  |
| Cardboard | 525 190 |  |  |
| Future- Sustainable Plastic | PS | 1 672 | kg |  |
| Pots (PP) | 65 091 | kg | Green Recycled |
| Trays (PP) | 57 795 | kg | Green Recycled |
| Sleeves (Recycled PE) | 100 981 | kg |  |
| Wrapping (LLDEPE) | 2 191 | kg |  |
| Other (PET) | 367 | kg |  |
| Cardboard | 525 190 | kg |  |

## Pellet Burner Scenario

Svegro switched from a bio-oil-based burner to two wood-pellet burners and auxiliary equipment to supply heat to the greenhouse. For this change, added infrastructure, i.e. a pellet furnace was included (see LCI dataset above). Furthermore, in the previous scenario, it was assumed that the bio-oil was tall oil (Ecoinvent dataset : market for tall oil, crude), as no other datasets for bio-oil were available. For the calculations of the energy density of the pellets and bio-oil, it was assumed that 1 tonne of pellets has a lower heating value of 4 800 kWh. In contrast, 1 m3 of bio-oil was assumed to have 8 925 kWh.

## Organic Fertilizers-2016

As outlined in the main text, in the scenario ‘Organic Fertlizers,’ Svegro converted from conventional to organic fertilizers. This entailed the development of a new system to deliver the organic fertilizer to the NFT system. Overall, this included adding nitrification tanks for the organic fertilizer, pumps, and filters. For the nitrification process, in total it was assumed that 5 additional water reservoirs were included (polyethylene IBU tanks) in addition to biofilm carriers in the tank to aid in the nitrification. These were assumed to be roughly 2 kg total per year of polyethylene per tank. For each take, a pump for aeration was also included, which was assumed to be a roughly 40W pump, requiring an additional 60 kWh of electricity annually. The organic fertilizers are developed based on food industry by-products. Due to proprietary reasons, the source of the organic fertilizer is withheld in the article. However, the authors can provide information upon request.

## Future-Biofuel Transport

As identified in the main text, in the Current scenario, roughly 62% of the fuel employed in transportation is assumed to be biofuel (i.e. FAME). For the Future-Biofuel Transport scenario, instead, it is assumed that all transportation by truck is fueled with a mix of biodiesel (FAME) and Hydrotreated vegetable oil (HVO), i.e. 50% of each. Life cycle inventory data for transportation by truck are taken from Ecoinvent datasets (see above) and those provided by the Network for Transportation Measures (NTM) database[[1]](#footnote-1) which provides datasets for Swedish transportation and fuel mixes.

## Future-Densify

For the Future-Densify scenario, additional gutters are added to the growing space. This is done by reducing the space between the gutters in order to accommodate for added gutters. Figure S1 provides a depiction of this densification process, while Figure 1 in the main text also provides a depiction of plants in the gutters. The production output would increase from roughly 20 330 000 to 30 500 000 plants annually

 For this scenario, it is assumed that a linear increase in all inputs, e.g. water, nutrients, growing media, seeds, etc. are required. Additionally, it is assumed that no additional heating or lighting is required, as tests in one of the greenhouse chambers have suggested that these are sufficient.



Figure S: Top-view of gutters in the NFT system. The pictures depict a) original system with larger spacing between gutters, and b) depiction of the gutters with reduced spacing between as studied in the Future-Densification scenario.

# Lighting and Heating Assumptions

For the different scenarios, with specific application in the Future-LED scenario, HPS and LED lighting fixtures were modeled based on data available in Zhang et al. (2017). Table S2 provides an overview of the materials and components, in addition to the weight, per fixture or armature. Each LED armature is assumed to have an effect of roughly 650 W, while each HPS light of roughly 1.25 kW. In the assessment, the assumed lifetime of the HPS lights was 10 000 hours while the LEDs were assumed to have a lifetime of 50 000 hours. At the end of the lifetime, the bulbs (in the case of the HPS lights) can be changed, while the LED armatures are assumed to be replaced after this period. For the study, we considered the overall lifetime of the materials in each system to have a lifetime of 30 years. Currently, an installed effect of roughly 7.9 MW is in place at Svegro. In total, there are roughly 6 400 HPS light fixtures in place at Svegro. In total, roughly 5800 LED fixtures with a rating of 650 W are assumed to be needed in the greenhouse.

## Material Inputs for HPS and LED Lighting Fixtures

Table S4 provides a review of the assumptions for different materials used for the lighting fixtures. These values are based on Zhang et al. (2017).

*Table S4: Material Assumptions for the HPS and LED light fixtures based on Zhang et al. (2019. The table also includes the LCI datasets employed from Ecoinvent v. 3.7*

|  |  |  |  |
| --- | --- | --- | --- |
|  | Material | Amount (kg) | LCI Dataset |
| HPS Light Fixture | Aluminum | 2.41 | market for aluminium alloy, AlLi | aluminium alloy, AlLi | Cutoff, S |
| PVC | 0.825 | market for polyvinylchloride, bulk polymerised | polyvinylchloride, bulk polymerised | Cutoff, S |
| Ceramic | 0.11 | market for sanitary ceramics | sanitary ceramics | Cutoff, S |
| Steel | 0.15 | market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S |
| Electronics | 9.55 | market for capacitor, electrolyte type, > 2cm height | capacitor, electrolyte type, > 2cm height | Cutoff, S |
| LED Light Fixture | Aluminum | 9.3 | section bar extrusion, aluminium | | Cutoff, S  |
| Copper | 0.042 | market for copper | copper | Cutoff, S |
| PE | 0.127 | market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, S |
| Electronic | 0.1 | market for electronic component, passive, unspecified | electronic component, passive, unspecified | Cutoff, S |
|  | Light Emitting Diodes | 0.025 | market for light emitting diode | light emitting diode | Cutoff, S |

## Lighting and Heating Demand

The energy consumption for the scenarios was based on the baseline scenario and calculations for energy consumption of transitioning to LEDs from HPS lighting from Katzin et al. (2021). The energy consumption from the LEDs was based on similar photosynthetic photon flux density (PPFD) of 175 µ-mol/m2. For the study, we employed the following equations to study the implications of a transition from HPS to LEDs.

|  |  |
| --- | --- |
| $$E^{HPS}= Q\_{Light}^{HPS}+Q\_{Heat}^{HPS}$$ | *(1)* |

In Equation 1, $E^{HPS}$ denotes the total energy for the greenhouse, for lighting and heating. This includes $ Q\_{Light}^{HPS} the energy for lighting the greenhouse , in addition to Q\_{Heat}^{HPS} $is the energy use for heating the greenhouse with HPS lighting (which is the amount of heat from the pellet burner).

|  |  |
| --- | --- |
| $$E^{LED}= \frac{\in HPS}{\in LED}Q\_{Light}^{HPS}+Q\_{Heat}^{LED}$$ | *(2)* |

In Equation 2, the energy for heating and lighting the greenhouse with LEDs is $E^{LED}.$ Here, $Q\_{Heat}^{LED}$ is the amount of heat required for the greenhouse with LED lights (which again is increased due to less heat output from the LED lighting). For this study, we assumed an average increase in heat demand to be roughly 25% higher throughout the year based on information provided by the case study greenhouse and also in Katzin et al. (2021). This is reflected in the scenario for LEDs by increased heat from the pellet burner. In this study, the variables ∈HPS and ∈LED are assumed to be 1.8 and 3.5 µ-mol/J for the different lighting systems respectively. The ∈LED has been set to 3.5 according to Kusuma et al. (2020) that reported, for the current LED performances of a lamp with red and blue fixtures a maximum ∈ of 4.1µ-mol/J and 3.4 µ-mol/J for a lamp with white and red fixtures.

# Extended LCIA Results

Extended details for the different scenarios, including all ILCD impact categories, are provided in the supplementary excel file. This contains separate tabs to illustrate the different reviewed scenarios and associated environmental impacts, split into different processes. For the tables, in order to save space, acronyms are used for the impact category names. These include CC-Global Warming Potential, IR-Ionizing Radiation, RD-Mineral, Fossil & Renewable Resource Depletion, OD-Ozone Depletion, Meut-Marine Eutrophication, WRD-Water Resource Depletion, AP-Acidification, POCP-Photochemical Ozone Formation, LU-Land Use, IRH-Ionizing Radiation HH, Feco-Freshwater Ecotoxicity, FE-Freshwater Eutrophication, TE-Terrestrial Eutrophication, HT-C-Human Toxicity, Cancer Effects, PM-Particulate Matter, HT-NC- Human Toxicity, Non-Cancer Effects.

# References

Ecoinvent, 2018. Ecoinvent LCI database v. 3.8.

Katzin, D., Marcelis, L.F.M., van Mourik, S., 2021. Energy savings in greenhouses by transition from high-pressure sodium to LED lighting. Applied Energy 281, 116019.

Kusuma, P., Pattison, P.M., Bugbee, B., 2020. From physics to fixtures to food: current and potential LED efficacy. Horticulture Research 7.

Zhang et al, 2018. A comparative life cycle assessment (LCA) of lighting technologies for greenhouse crop production. Journal of Cleaner Production 140, 705-713.

1. www.transportmeasures.org [↑](#footnote-ref-1)