Lowering your emissions through innovation in transport and energy infrastructure

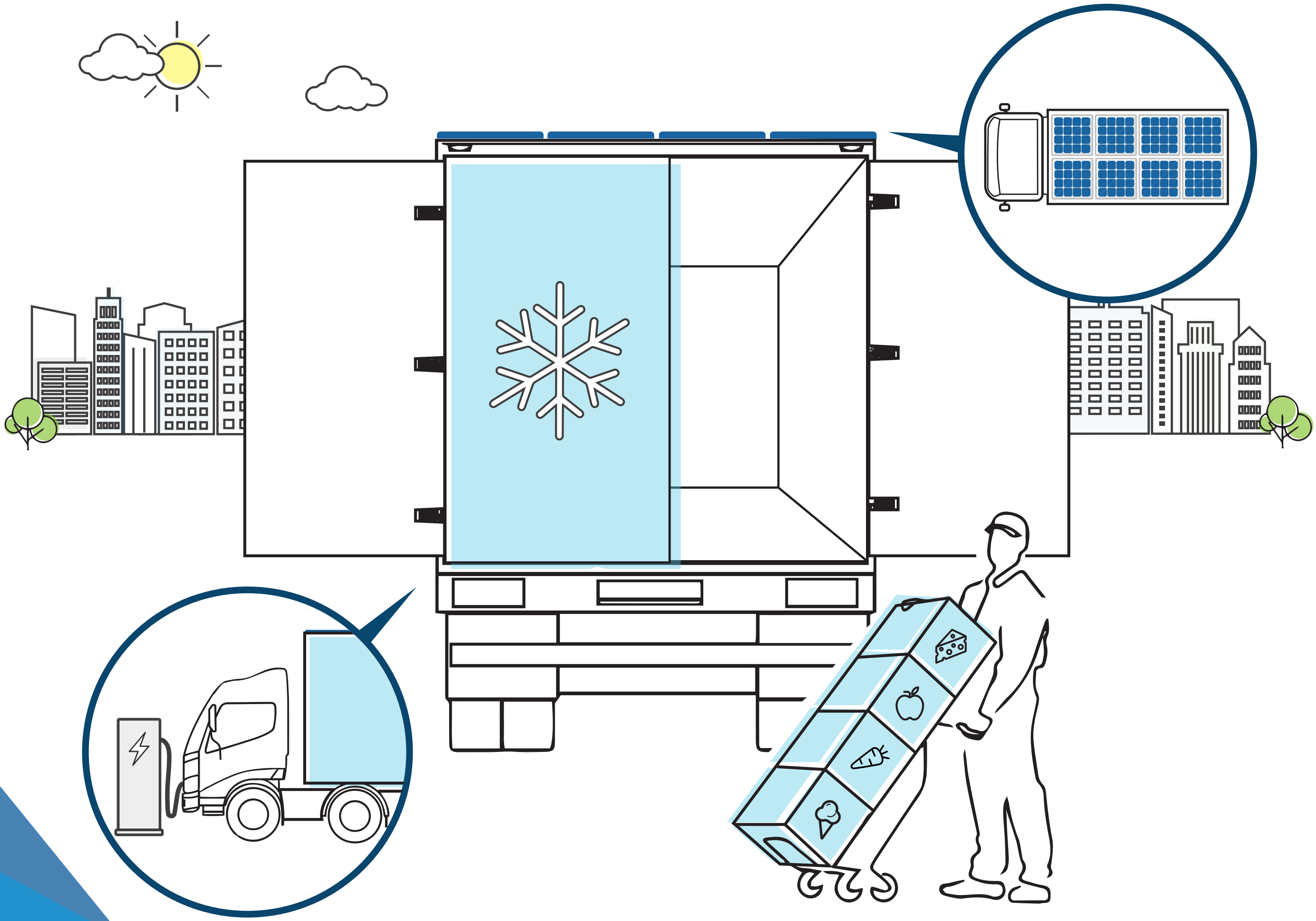
Transport

Energy Infrastructure

Knowledge & Enterprise

Project ZERO:

Techno-economic and Environmental Modelling



SUNSWAP

Innovate UK

August 2021

Infographic Summary

While our transport sector moves to lower emission vehicles, the diesel auxiliary engines, which provide power to the refrigeration units on vehicles, continue to pollute more than the vehicles' main engine.

This second Cenex white paper from project ZERO (Zero Emission Refrigerated Operations) provides an independent modelled assessment of alternative electrical transport refrigeration technology being developed by Sunswap. The Cenex modelling process, outlined below, aimed to prove the operational, environmental and economic feasibility of Sunswap's transport refrigeration technology.

ENERGY MODELLING METHOD

- Refrigeration demand modelling
- Electrical supply modelling

DUTY CYCLE DEVELOPMENT

- Definition of duty cycle phases
- Definition of duty cycle intensities

ENERGY MODELLING RESULTS

- Seasonal variance of energy demand & supply
- Daily variance of energy demand & supply
- Battery capacity requirement

ECONOMIC ANALYSIS

- Total cost of ownership breakdown
- Payback period and savings vs diesel

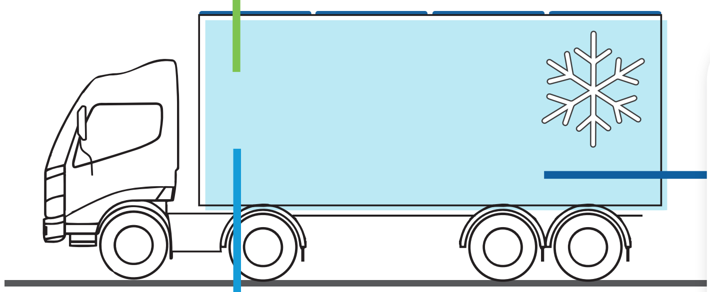
ENVIRONMENTAL IMPACT ASSESSMENT

- Production and use phase emissions
- Life cycle assessment (LCA) impact vs diesel

Results of the modelling included:

Energy modelling:

- **Transmission and infiltration losses dominate thermal demand**
- **Solar PV enables reduction in battery size required by 6-15 kWh**



Life cycle assessment (LCA):

- **Production phase: -34 to +45% difference in climate change impact (depending on battery size)**
- **Use phase: reduction of 79 to 93% in GHG WTW emissions, 100% reduction in NOx and PM**

Economic analysis:

- **Higher capital expenditure of the Sunswap system is recovered due to its lower operating expenditure compared to diesel**
- **From 2022, seven-year TCO savings between 20 and 50% compared to diesel**
- **Multi-compartment operation from 2022 achieves payback in 2 to 4 years**

Next steps:

The current electrical novel system has been recently tested at Sunswap's facilities. The system is due to be trialled with UK fleets at the end of 2021 to prove the modelled results shown in this report.

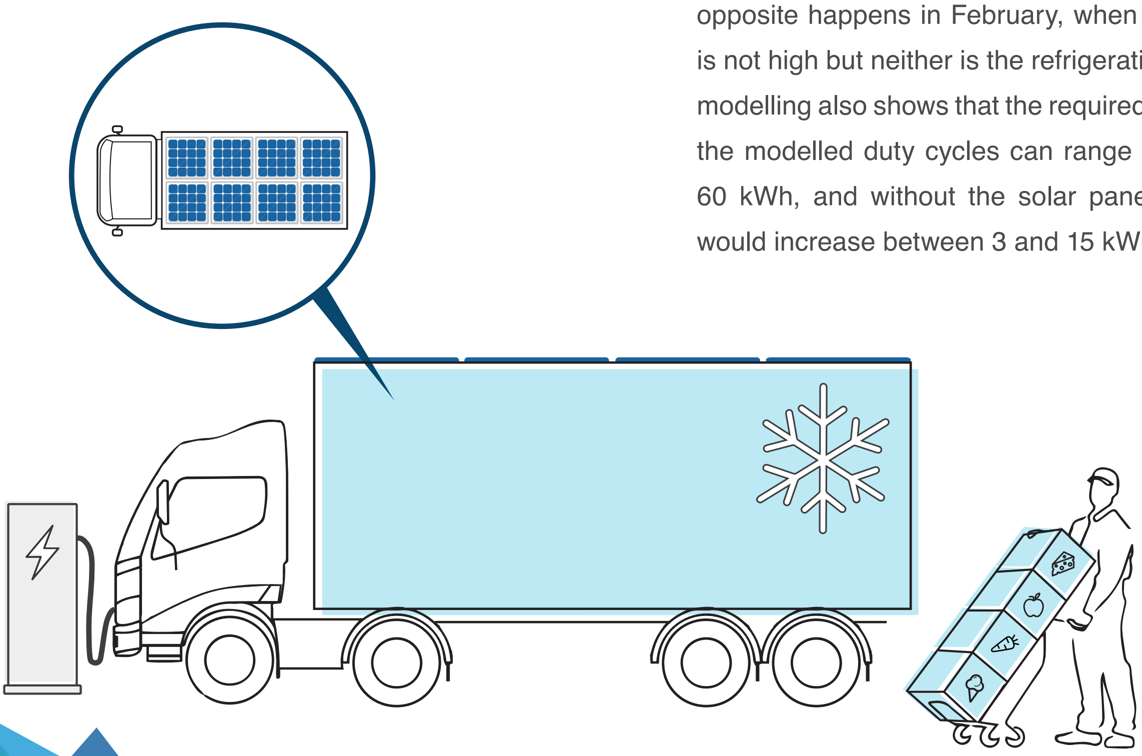
Executive Summary

This white paper presents the methodology and results of the techno-economic and environmental modelling that Cenex has conducted of the Sunswap's transport refrigeration technology and a comparative diesel one. This is the second of two white papers that we have released as part of project ZERO (Zero Emission Refrigerated Operations). The first paper introduced refrigerated transport and its emissions, and gave insights into best practice for fleets and clean alternatives. This second paper gives the independent modelled assessment of the Sunswap technology by Cenex to prove its operational, environmental and economic feasibility.

The energy modelling was performed separately for the refrigeration demand and the electrical supply. The refrigeration demand is caused by heat lost to the ambient through the trailer walls and when the trailer doors are opened. The electrical supply model considers the solar energy available for different times of day, and months of a year. Both models are then linked to calculate the grid charging demand, the required battery size, and the diesel equivalent requirements.

We modelled duty cycles of different intensities and a variety of products (and therefore required temperatures) based on feedback from refrigerated transport operators. The duty cycles are split into trailer precooling to the desired temperature, product loading, driving to destination, and product unloading. This process is typically repeated between two and four times per day.

The energy modelling shows that, throughout the year, the refrigeration demand is well aligned with the solar supply. In July, the energy demand is the highest due to the high ambient temperatures, but the solar supply is also very high due to the long daylight hours, reduced cloudiness and favourable solar irradiation angles. The opposite happens in February, when the solar supply is not high but neither is the refrigeration demand. The modelling also shows that the required battery sizes for the modelled duty cycles can range between 20 and 60 kWh, and without the solar panels these figures would increase between 3 and 15 kWh.



Executive Summary

The capital expenditure of the Sunswap system is higher than a comparator diesel one, but the operational expenditure is significantly lower due to reduced maintenance and fuel costs (especially after the removal of red diesel subsidy from 2022). For this reason, the estimated total cost of ownership (TCO) savings of the Sunswap system after 7 years range between 20 and 50% compared to diesel. Therefore, under the assumptions of the models, a typical supermarket multi- compartment operation can achieve payback of the initial investment in 2 to 4 years.

The environmental modelling followed the life cycle assessment (LCA) method, which accounts for the environmental impact of the whole life of the product, from production through the use phase until the end of life. The global warming impact of the production phase can range from a 34% reduction compared to diesel with a 20-kWh battery, to a 45% increase with a 60-kWh battery. However, the use phase savings of global warming impact range between 79 and 93% compared to diesel. This is due to the use of electricity and the use of a lower global warming potential (GWP) refrigerant in the Sunswap system. Moreover, the Sunswap system offers 100% air quality savings in the use phase. The end-of-life impact was negligible compared to the production and use phases. The modelled total LCA global warming impact of the Sunswap system is 77 to 93% less than diesel and there are major savings in most of the other environmental impact categories.

In conclusion, Cenex has independently modelled the use of the Sunswap system under a range of typical food delivery scenarios and verified that the technology has the potential to offer significant environmental and economic savings compared to diesel systems, and that it is a viable alternative solution to current highly polluting diesel refrigeration systems.

The current electrical novel system has been recently tested at Sunswap's facilities. The next steps will be to trial the system with UK fleets at the end of 2021 and prove the modelled results shown in this report.

Introduction

This is the second white paper released as part of the Innovate UK funded project ZERO: Zero Emission Refrigerated Operations. The first paper provided an introduction to refrigerated transport and its current high emissions, and also informed about clean alternatives and best practice tips for fleets.

This second paper exposes the independent assessment of the Sunswap technology by Cenex to prove its operational, environmental and economic feasibility.

The large environmental impact of current transport refrigeration units (TRUs), the financial consequences of the removal of red diesel subsidies, plus tightening legislation and corporate social responsibility, all mean that customers require a clean and economical alternative. The solution proposed by the project was to replace the diesel TRU with a solar and battery powered system. At the core of the product is the patent-pending battery technology enabling the TRU to meet a wide range of customer requirements. Additionally, the trailer roof is covered with solar panels, providing extra on-board energy.

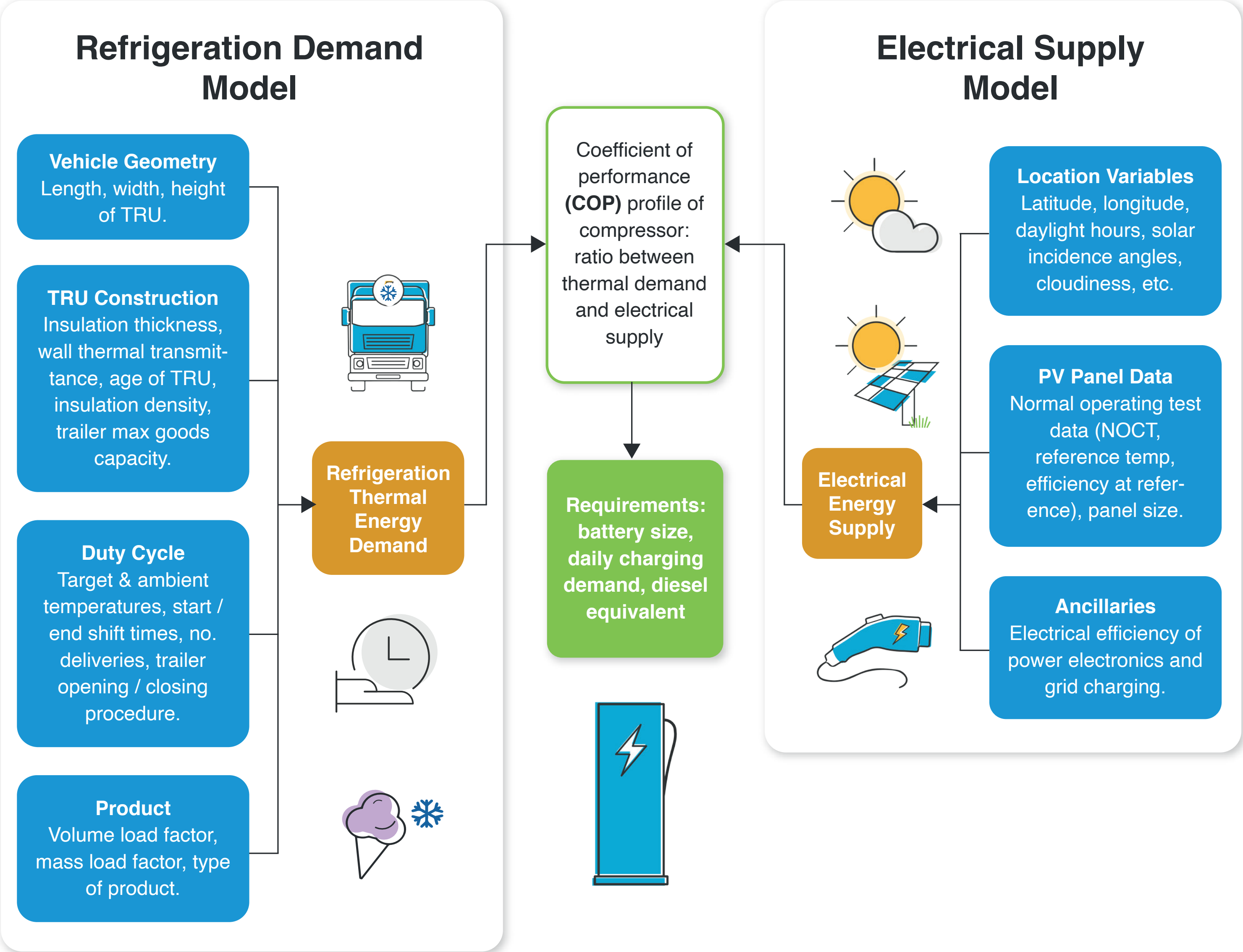
Sunswap is a start-up developing electric transport refrigeration technology utilising energy prediction software, adaptive battery capacity and solar power to decarbonise the cold chain. Cenex, established as the UK's first Centre of Excellence for Low Carbon and Fuel Cell technologies in 2005, operates as an independent, not-for-profit research & technology organisation (RTO) and consultancy which aims to lower emission in transport and associated energy infrastructure.

Cenex's role in project ZERO was to investigate the customer needs and independently validate operational design requirements, as well as the techno-economic and environmental performance of the system. As part of this role, Cenex formed a customer requirements group to understand the needs and operational patterns of refrigerated transport operators and vehicle builders. Moreover, Cenex also developed a refrigerated fleet techno-economic model, as well as a life-cycle assessment (LCA) model to calculate the emissions associated with the product manufacturing, use and end-of- life phases. The results from this modelling are presented in this paper. The modelling work has informed Sunswap's development to refine the design of their TRU electrical system.

This report is a modelled feasibility study and does not show physical tested results. The next generation system is currently being tested, but will be moving forward to trials with fleets at the end of 2021.

Please note: Cenex has conducted an impartial and independent assessment of Sunswap's transport refrigeration technology via our own models developed in this project. These are not linked to the Sunswap Analytics^{TM} software, which is used to accurately evaluate each customer's need on a case- by-case basis. The results shown in this paper have been obtained from modelling the Sunswap system in a theoretical environment.

Modelling Methodology



Refrigeration Demand Model

Vehicle Geometry
Length, width, height of TRU.

TRU Construction
Insulation thickness, wall thermal transmittance, age of TRU, insulation density, trailer max goods capacity.

Duty Cycle
Target & ambient temperatures, start / end shift times, no. deliveries, trailer opening / closing procedure.

Product
Volume load factor, mass load factor, type of product.

Refrigeration Thermal Energy Demand

Coefficient of performance **(COP)** profile of compressor: ratio between thermal demand and electrical supply

Requirements: battery size, daily charging demand, diesel equivalent

Electrical Supply Model

Location Variables
Latitude, longitude, daylight hours, solar incidence angles, cloudiness, etc.

PV Panel Data
Normal operating test data (NOCT, reference temp, efficiency at reference), panel size.

Ancillaries
Electrical efficiency of power electronics and grid charging.

Electrical Energy Supply

Cenex has developed the following models using publicly available data and literature. Sunswap also provided performance data, but we have ensured that the models remained independent and impartial. The high-level energy flows and models are represented in the diagram above.

The refrigeration demand and electrical supply are calculated separately in different models. The refrigeration demand model focuses on the energy exchange happening between the trailer interior and the exterior, including the interaction between the cold produce and its surroundings. The solar supply model focuses on the electrical equipment attached to the trailer, i.e. the solar photovoltaic (PV) system, battery packs and ancillaries.

Refrigeration Demand Model

The trailer specifications are necessary in the demand model to understand the volume of air and amount of product to be refrigerated, as well as its insulation characteristics to calculate the thermal losses to the ambient. The duty cycle information is also key to factor in the daily hours the fridge needs to operate, the number of times the trailer doors need to open, daily number of deliveries, ambient temperature, etc. Finally, the product characteristics are required to account for its refrigeration temperature, its density, and its respiration heat if applicable.

The refrigeration demand model uses these inputs to calculate the thermal loads required to chill or freeze the produce, and it accounts for the following loads:

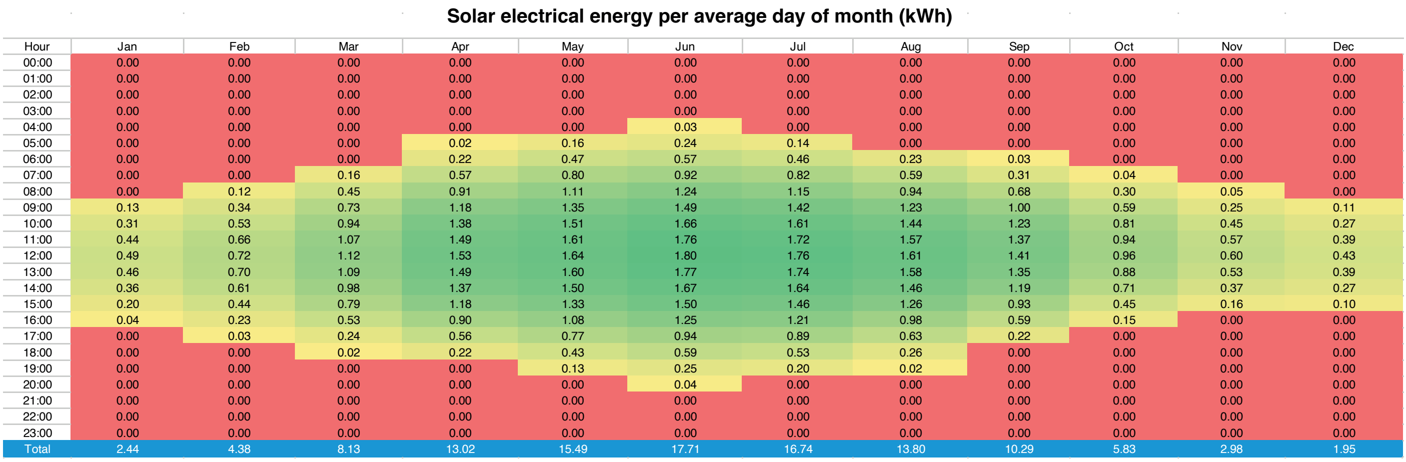
- **Infiltration load:** Heat loss to ambient that occurs within the product, air volume, and fridge walls when the trailer doors are opened. Usually the highest load, hence why it is important to minimise door opening times and frequencies.
- **Transmission load:** Thermal losses to the ambient through the trailer walls, roof and floor. Usually the second highest load. These occur whenever the ambient temperature is higher than the trailer interior.
- **Precooling load:** Before loading the vehicle with produce at the depot or supermarket, the TRU needs to pre-cool the thermal mass of the trailer walls and the volume of air inside from ambient to the target temperature to avoid breaking the cold chain of the produce.
- **Product load:** Heat of respiration generated by fruits and vegetables, which transform oxygen into heat, carbon dioxide and water vapour.

Electrical Supply Model

Firstly, the solar supply model needs to account for the geographical location of the trailer, as this has an influence in the ambient temperature (accounted for in the demand model), number of daylight hours, solar irradiation characteristics and weather (cloudiness, humidity, etc.). Moreover, we need to consider the solar PV technical specifications, such as its efficiency at different temperatures, its size and other features that come from manufacturer testing. Finally, the efficiencies of electronic components and charging equipment need to be factored in.

The solar supply model is based on the “Tau” revised clear sky model calculations from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). The Tau model equations are initially used to estimate hourly clear-day solar radiation for any month of the year in the northern hemisphere. Using this model, we account for the seasonal changes in the dust and water vapor content of the atmosphere and the changing earth-sun distance. Then, we use the additional Tau model factors that are based on location-specific optical depths for direct and diffuse radiation, which account for cloudiness and are tabulated by month for 5,564 weather stations around the world. The Cenex model then approximates the values to the closest weather station to the desired trailer location. Last but not least, shading factors are considered and obtained using the EU Commission’s Photovoltaic Geographical Information System.

The shape and inclination of the solar panels and varying location of the trailer can also be accounted for. In this application, we assumed flat solar panels covering the whole trailer roof surface at a fixed location in East London. The daily electrical energy obtained from the PV system is shown in the **figure below** for a typical day of each month:



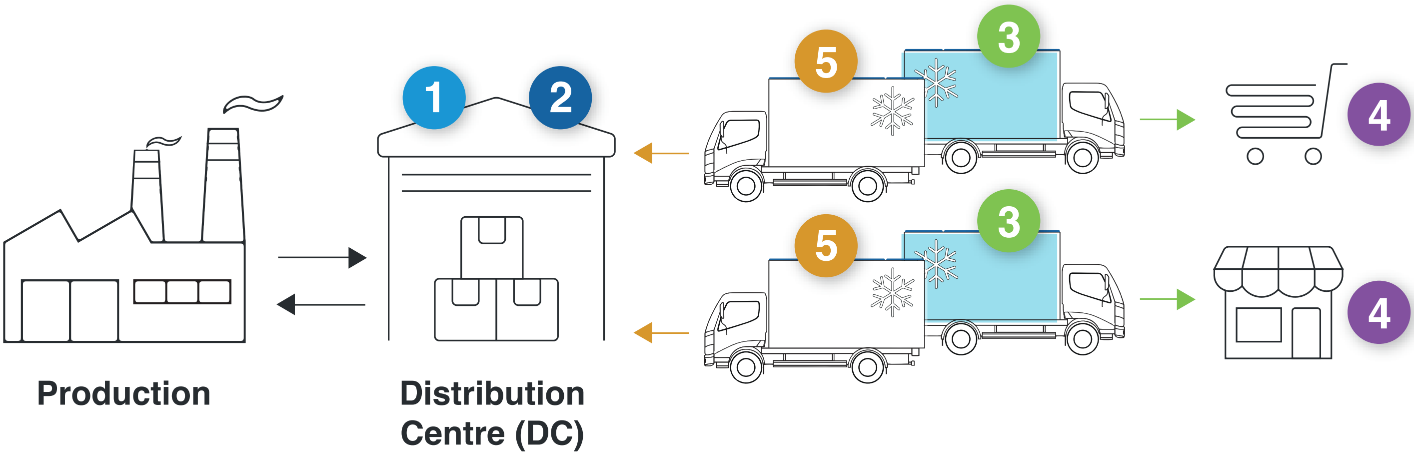
Solar electrical energy per average day of month (kWh)

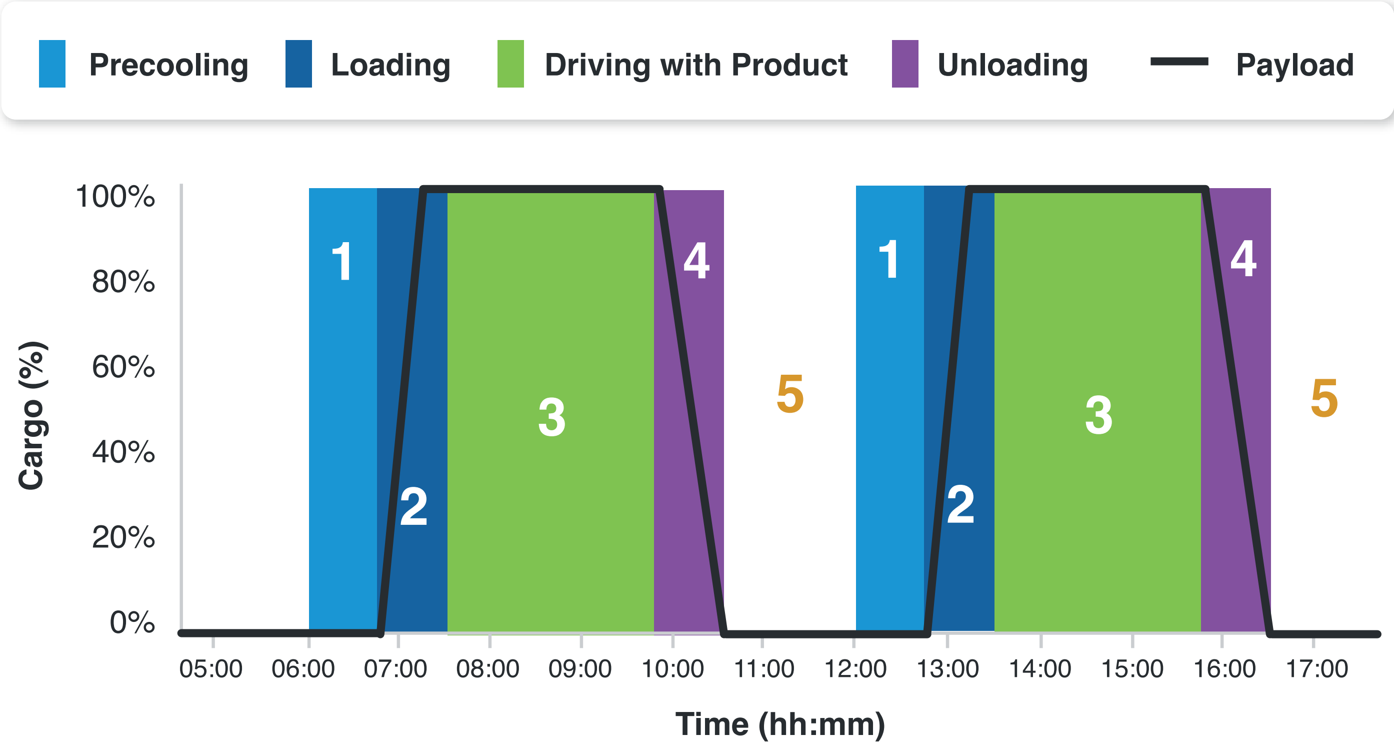
Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
01:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
02:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
03:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
04:00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00
05:00	0.00	0.00	0.00	0.02	0.16	0.24	0.14	0.00	0.00	0.00	0.00	0.00
06:00	0.00	0.00	0.00	0.22	0.47	0.57	0.46	0.23	0.03	0.00	0.00	0.00
07:00	0.00	0.00	0.16	0.57	0.80	0.92	0.82	0.59	0.31	0.04	0.00	0.00
08:00	0.00	0.12	0.45	0.91	1.11	1.24	1.15	0.94	0.68	0.30	0.05	0.00
09:00	0.13	0.34	0.73	1.18	1.35	1.49	1.42	1.23	1.00	0.59	0.25	0.11
10:00	0.31	0.53	0.94	1.38	1.51	1.66	1.61	1.44	1.23	0.81	0.45	0.27
11:00	0.44	0.66	1.07	1.49	1.61	1.76	1.72	1.57	1.37	0.94	0.57	0.39
12:00	0.49	0.72	1.12	1.53	1.64	1.80	1.76	1.61	1.41	0.96	0.60	0.43
13:00	0.46	0.70	1.09	1.49	1.60	1.77	1.74	1.58	1.35	0.88	0.53	0.39
14:00	0.36	0.61	0.98	1.37	1.50	1.67	1.64	1.46	1.19	0.71	0.37	0.27
15:00	0.20	0.44	0.79	1.18	1.33	1.50	1.46	1.26	0.93	0.45	0.16	0.10
16:00	0.04	0.23	0.53	0.90	1.08	1.25	1.21	0.98	0.59	0.15	0.00	0.00
17:00	0.00	0.03	0.24	0.56	0.77	0.94	0.89	0.63	0.22	0.00	0.00	0.00
18:00	0.00	0.00	0.02	0.22	0.43	0.59	0.53	0.26	0.00	0.00	0.00	0.00
19:00	0.00	0.00	0.00	0.00	0.13	0.25	0.20	0.02	0.00	0.00	0.00	0.00
20:00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00
21:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	2.44	4.38	8.13	13.02	15.49	17.71	16.74	13.80	10.29	5.83	2.98	1.95

Duty Cycles

In January 2021, Sunswap and Cenex held a workshop with several cold chain stakeholders, mostly supermarkets. These and other stakeholders have also filled in questionnaires during the project. During this process, we have collected feedback from the industry on refrigerated transport duty cycles, usage patterns, door opening procedures, TRU fuel use, compartment configurations, TRU maintenance requirements, etc.

Using this information, Cenex created the following representative duty cycles of the typical refrigerated transport operation of a supermarket. **This study focused on the retail side of the supply chain (rather than the production side), and the duty cycles are described in the following diagram:**





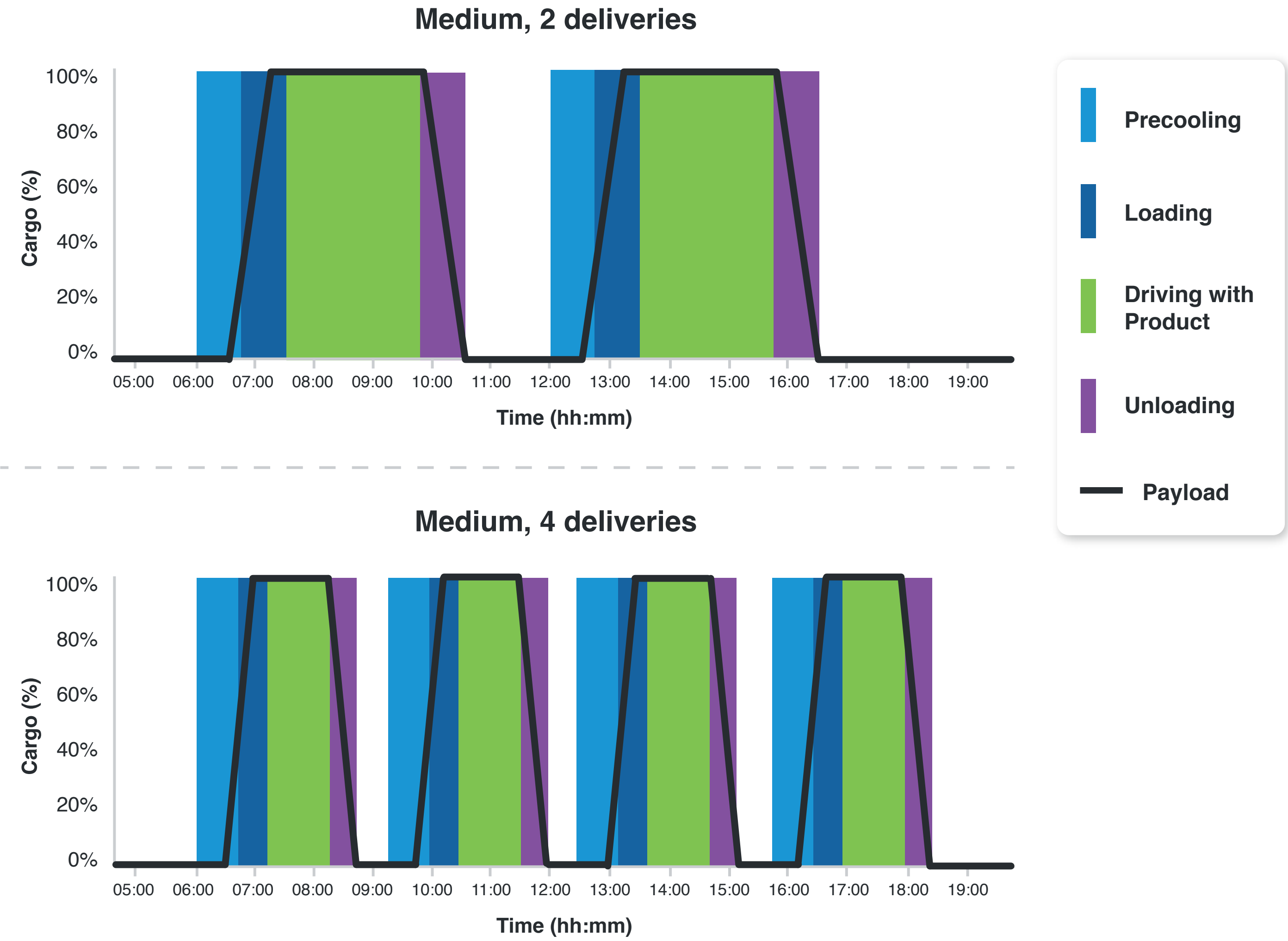
Initially, the trailer is precooled at the distribution centre (DC) and loaded with produce once the target refrigeration temperature has been reached. Then, the truck is driven to the shop or supermarket, where the produce is unloaded, and the truck is driven back to the distribution centre.

This process is then usually repeated two to four times per day. The representative duty cycles are described in the table below. We have chosen three different duty cycles because they capture well the variability of refrigerated transport operations.

DUTY CYCLE INTENSITY	LOW	MEDIUM	HIGH
Precooling, loading, waiting for tractor	1h 30m	1h 45m - 2h 15m	2h 15m - 2h 45m
Driving from DC to shop	30m	30m - 1h 30m	45m - 2h 45m
Unloading	30m	30m - 45m	45m
Driving from shop to DC	30m	30m - 1h 30m	45m - 2h 45m
Per cycle / delivery	**3h**	**3h 15m - 6h**	**4h 30m - 9h**
Number of cycles / deliveries per day	**2**	**2 - 4**	**2 - 4**
Per day	**6h**	**12 - 13h**	**18h**

Duty Cycles

The time taken for each duty cycle phase is variable depending on the duty cycle intensity, adding up to days lasting between 6 and 18 hours. The medium and high intensity duty cycles can have shorter drives (4 deliveries/day) or longer drives (2 deliveries/day). The trailer (un)loading procedure is the following: 15 minutes with the doors open while (un)loading and the TRU switched off, followed by 5 minutes with the doors closed and the TRU switched on to allow the trailer to re-cool before the (un)loading continues. The most representative duty cycle for supermarket operation is the medium intensity one, but they can operate all the ones described above. Examples of the medium intensity cycles are shown below:



We have modelled the following trailer configurations and temperatures (with examples of produce) as most representative of the industry:

- **Single compartment:**
  - 2°C: Low temperature fruits and vegetables
  - -18°C: Fishery products and deep frozen foods
  - -25°C: Ice and ice cream
- **Triple compartment:**
  -25°C, 2°C and ambient temperature.

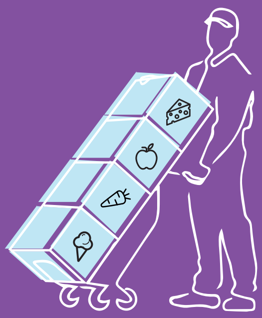
Modelling Assumptions

The following modelling assumptions were made:

- The focus was placed on retail duty cycles, i.e. from distribution centres to supermarkets/shops.
- The ambient temperature was assumed to be constant during a given day, but it changed with each month.
- The models consider the fact that TRUs are not functioning continuously when they have produce inside, as sometimes they can go into standby automatically if refrigeration is not required.
- The duty cycles include a time of 30 minutes to 1 hour during which loaded trailers wait for a tractor unit to arrive, as typically supermarkets operate with 30% more trailers than tractors.
- The modelled payload is 50% of the trailer capacity in mass and 100% in volume.
- The produce loading and unloading is carried out to ambient temperature and not to chilling bays, as not all supermarkets have these. This way we account for the worst-case energy demand scenario.
- The solar panels are flat and cover the whole trailer roof surface at a fixed location in East London.

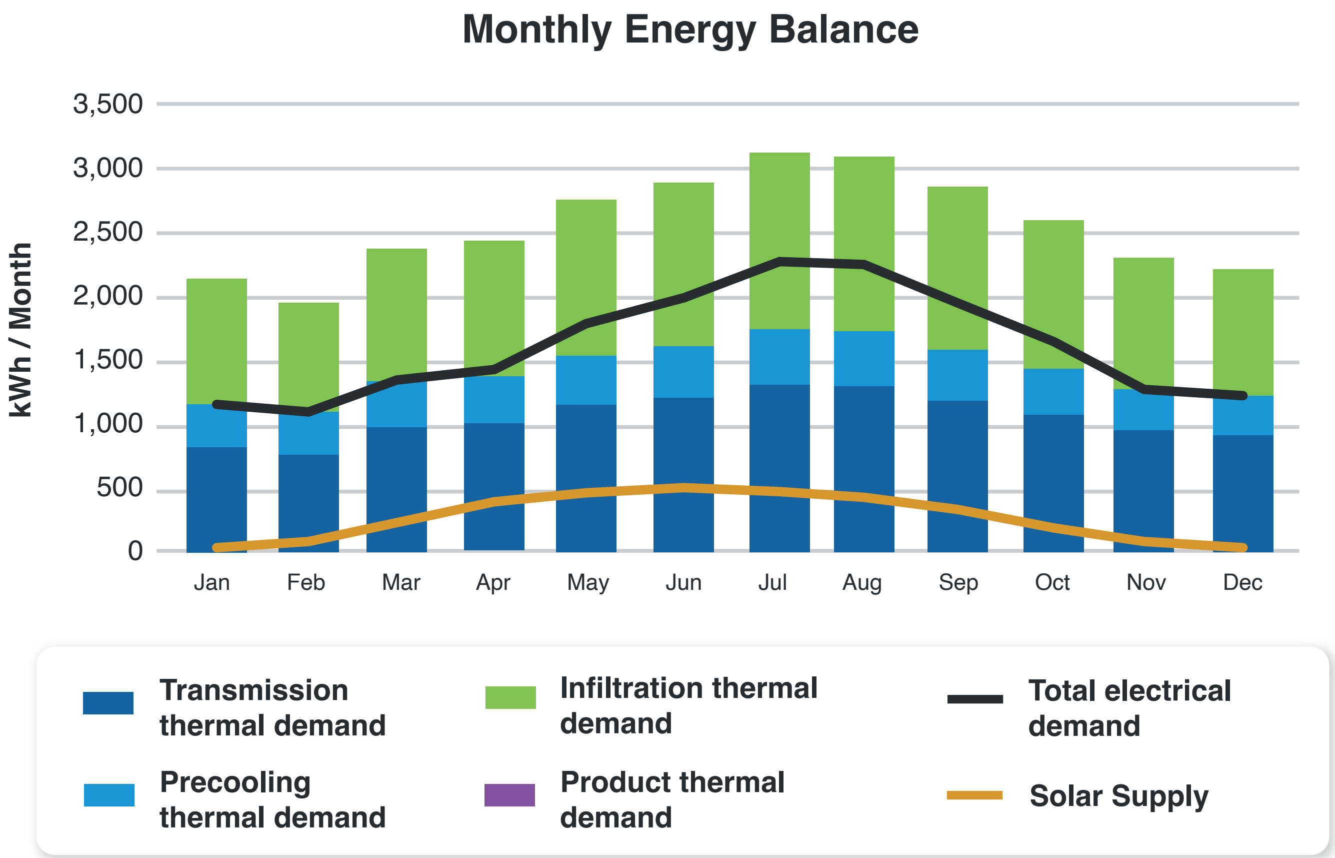
Energy Modelling

To represent the variability of refrigeration demand depending on operation, we have picked the following three energy intensity cases with specific trailer temperatures, durations and number of deliveries:



ENERGY INTENSITY CASE	HIGH	LOW	MEDIUM
Compartment	Single	Single	Triple
Trailer temperature	-25˚C (ice cream)	0˚C (low temp veg)	-25˚C, 0˚C & ambient
Duty cycle intensity	High (18 h/day)	Low (6 h/day)	Medium (13 h/day)
No. deliveries per day	4	2	4
Diesel equivalence	7,600 L/year	400 L/year	2,300 L/year

High Intensity Case



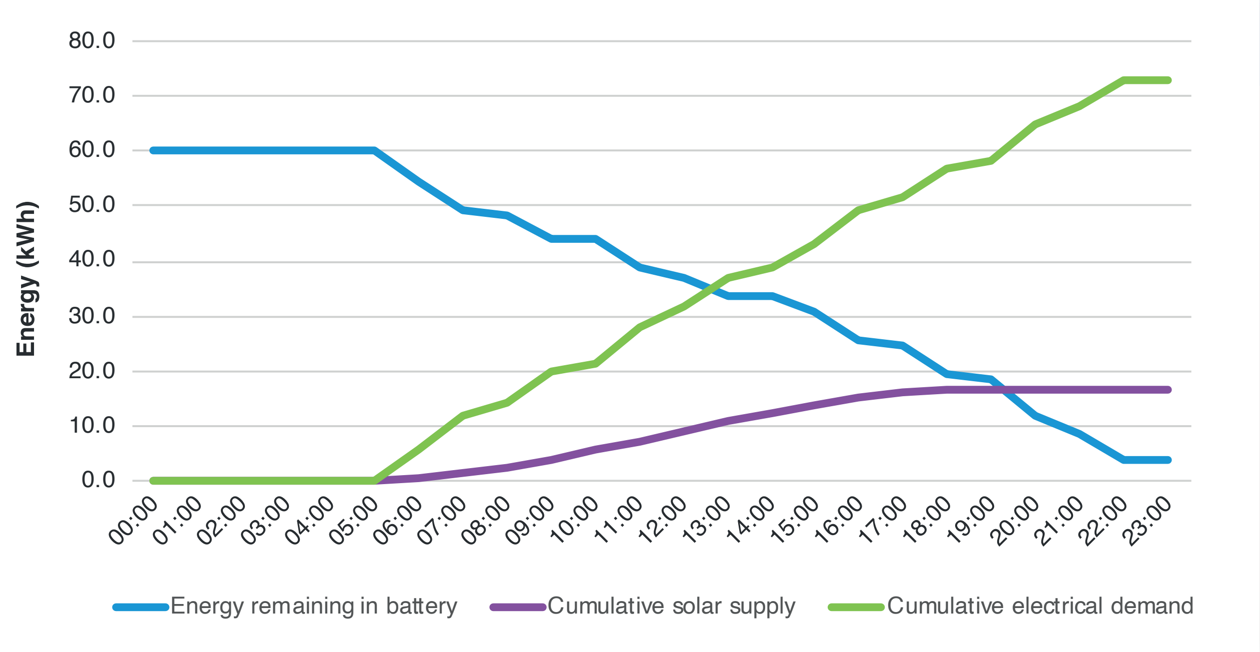
The bars in the graph above show the thermal demand split by type, while the lines show electrical solar supply and electrical refrigeration demand, which is related to the thermal demand by the system's coefficient of performance or COP.

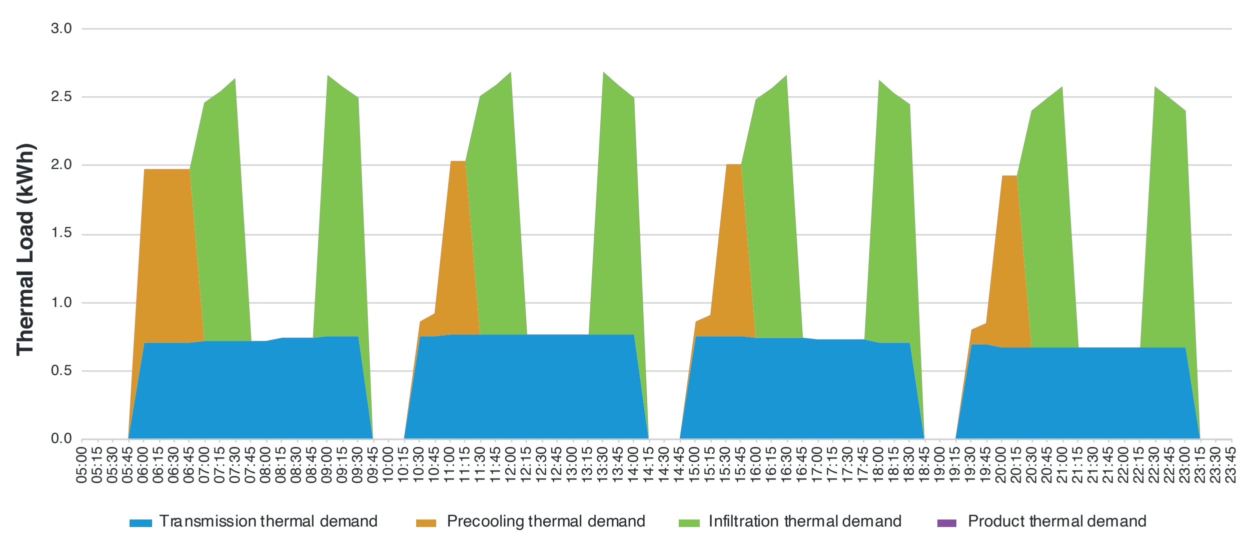
The energy demand is well aligned with the solar energy supply, with only a slight mismatch due to the higher daylight hours in June/July (which drives the solar supply), but higher ambient temperature in July/August (which drives refrigeration demand). Transmission and infiltration losses dominate the thermal demand, with about 40% of the demand each. The difference between the electrical demand and the solar supply needs to be supplied by charging the batteries from the grid.

The COP is the ratio of the thermal demand or useful heat removed by the refrigeration system, divided by the electrical supply or work required by the refrigeration system. It typically ranges between 0.9 and 4.5 and it is usually higher than 1 (the lower the difference between target and ambient temperature, the higher the COP). This happens because, instead of just converting work to heat, the system transfers additional heat from a heat source (the produce we want to chill/freeze) to where the heat is absorbed (the refrigerant fluid).

In order to show the extreme of the high intensity case, we zoom into one day of July, which is the month with the highest energy demand. Fortunately, it is also the month with the second highest solar energy supply.

Of the two graphs below, the bottom one shows the thermal energy demand by type for every 15-minute interval. The top graph shows the cumulative electrical energy demand, cumulative solar energy supply, and the energy remaining in the battery.

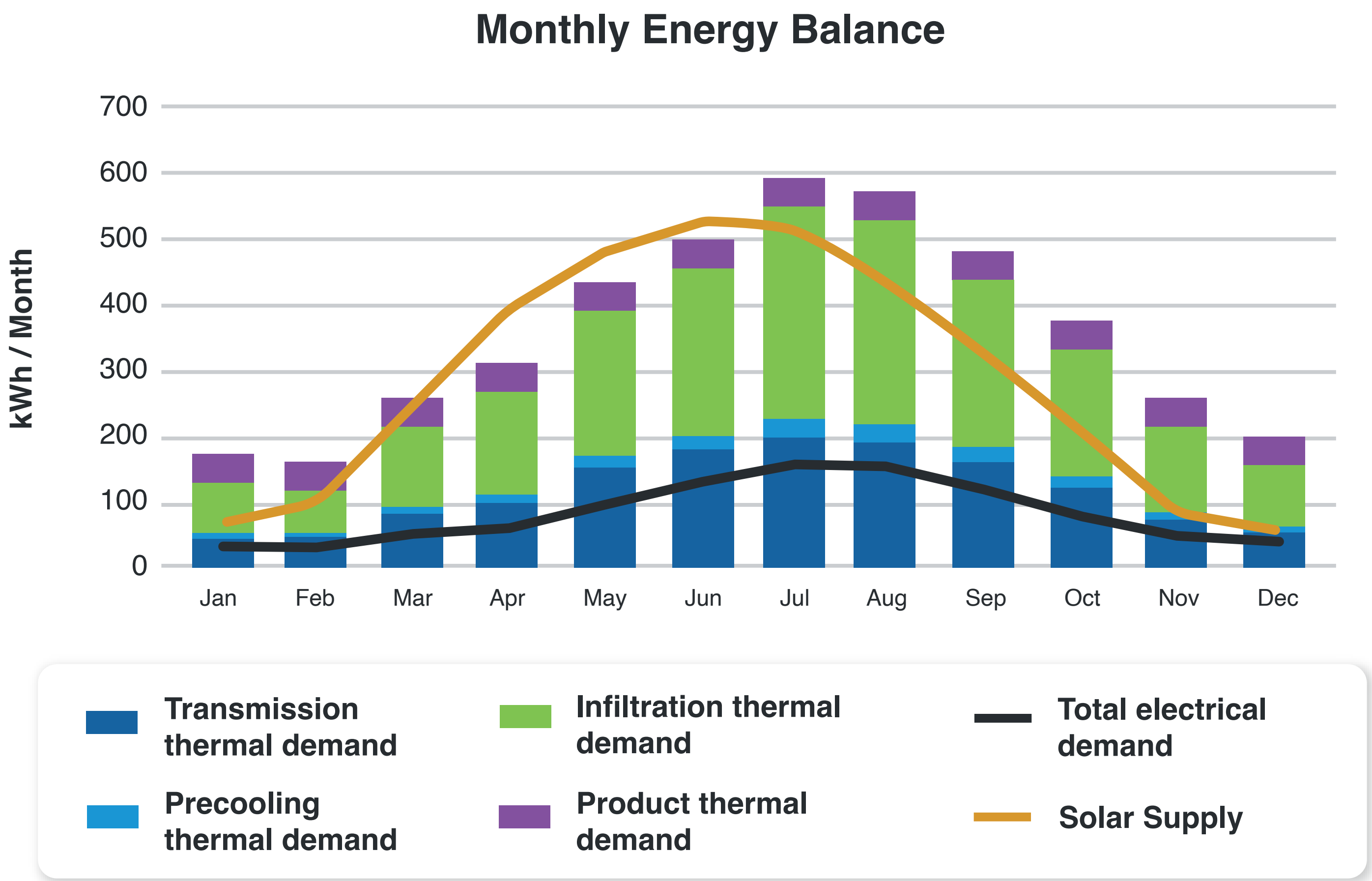




In the bottom graph, we can clearly appreciate the four cycles or deliveries that the trailer performs per day. The precooling load is lower in the second to fourth deliveries because the trailer keeps a lower temperature than ambient from the previous delivery. Additionally, the infiltration load only occurs when loading and unloading the trailer, and it is higher when there is more produce in the vehicle that loses heat when the doors are open.

In the top graph, we can observe that the cumulative solar energy supplied to the system is approximately 25% of the cumulative electrical demand required by the refrigeration. The energy drawn from the battery equals the difference between the cumulative values of electrical demand and solar supply. The reason why the battery is nearly depleted at the end of the day is that it has been sized for the most demanding month of the year, which in this case is July (the one we are showing on the graphs above).

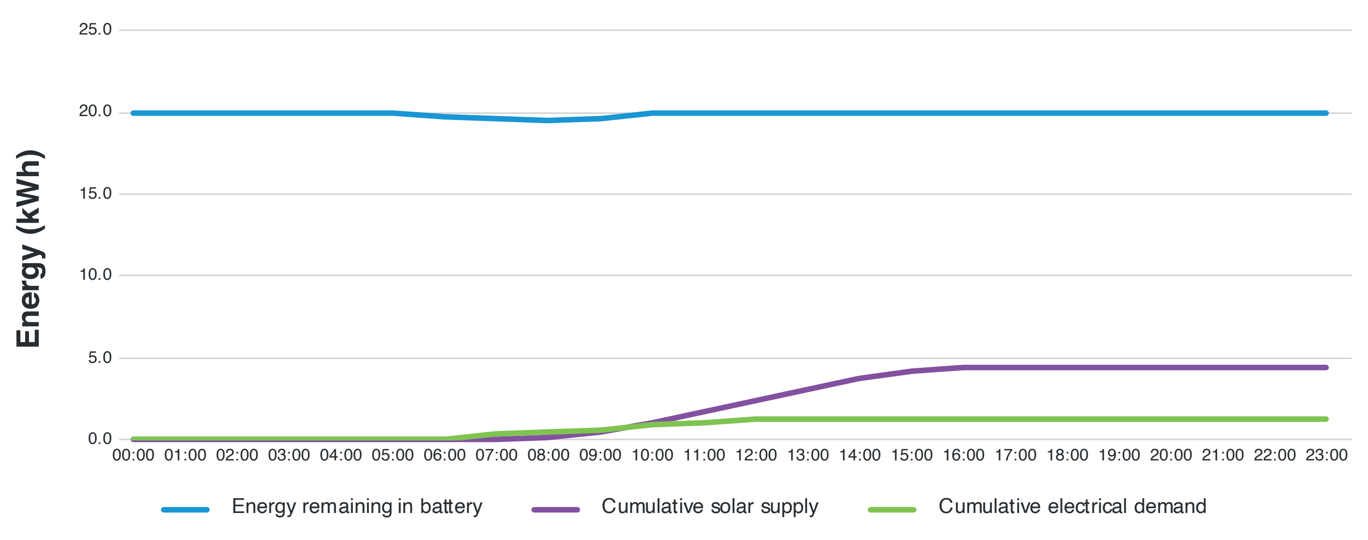
Low Intensity Case

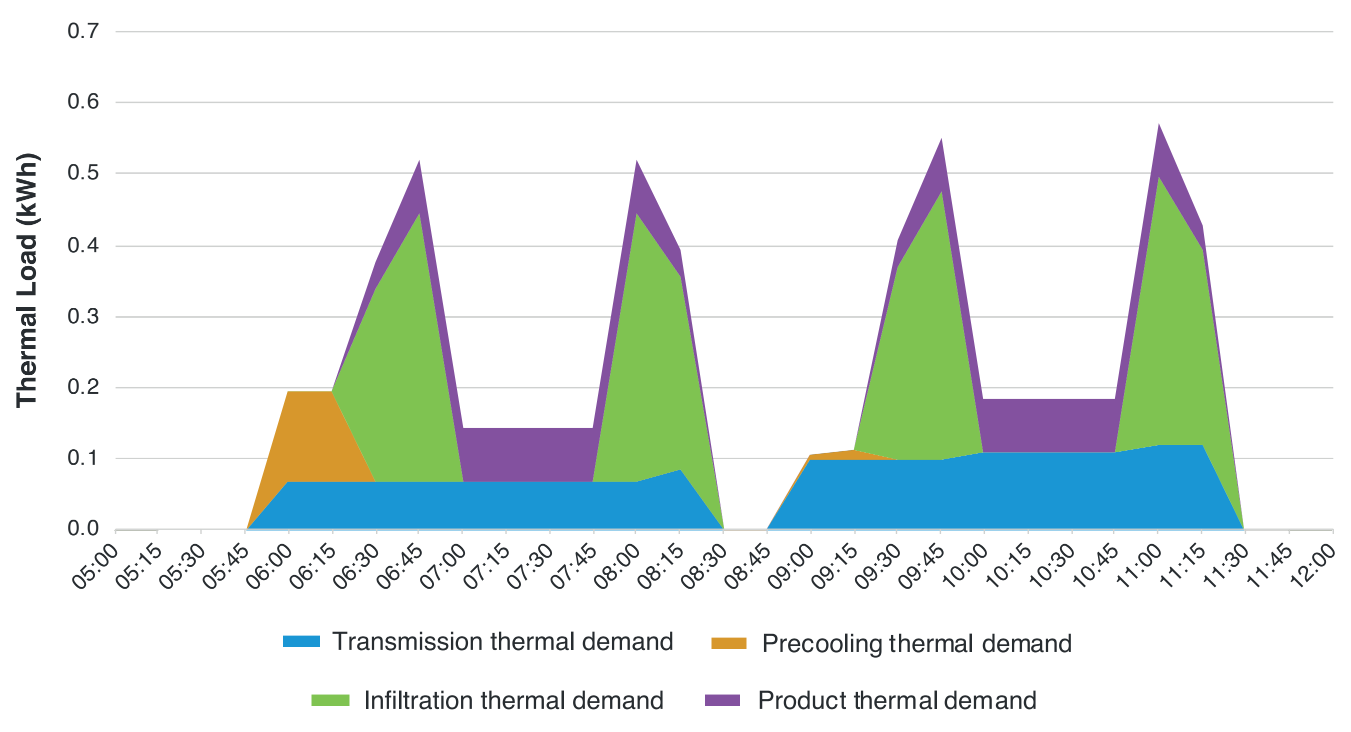


On the other extreme of intensity, we show firstly the seasonal variation in demand and supply in the graph above.

In this other extreme case, the refrigeration demand is relatively low for two reasons. Firstly, there are only two deliveries and six hours of operation per day. Secondly, the system COP in this case is higher than in the high intensity case, due to the smaller difference between target and ambient temperature (hence less electrical energy required per unit of thermal energy demand). The solar supply can by itself cover the electrical demand all year long without needing to plug in the system to the grid.

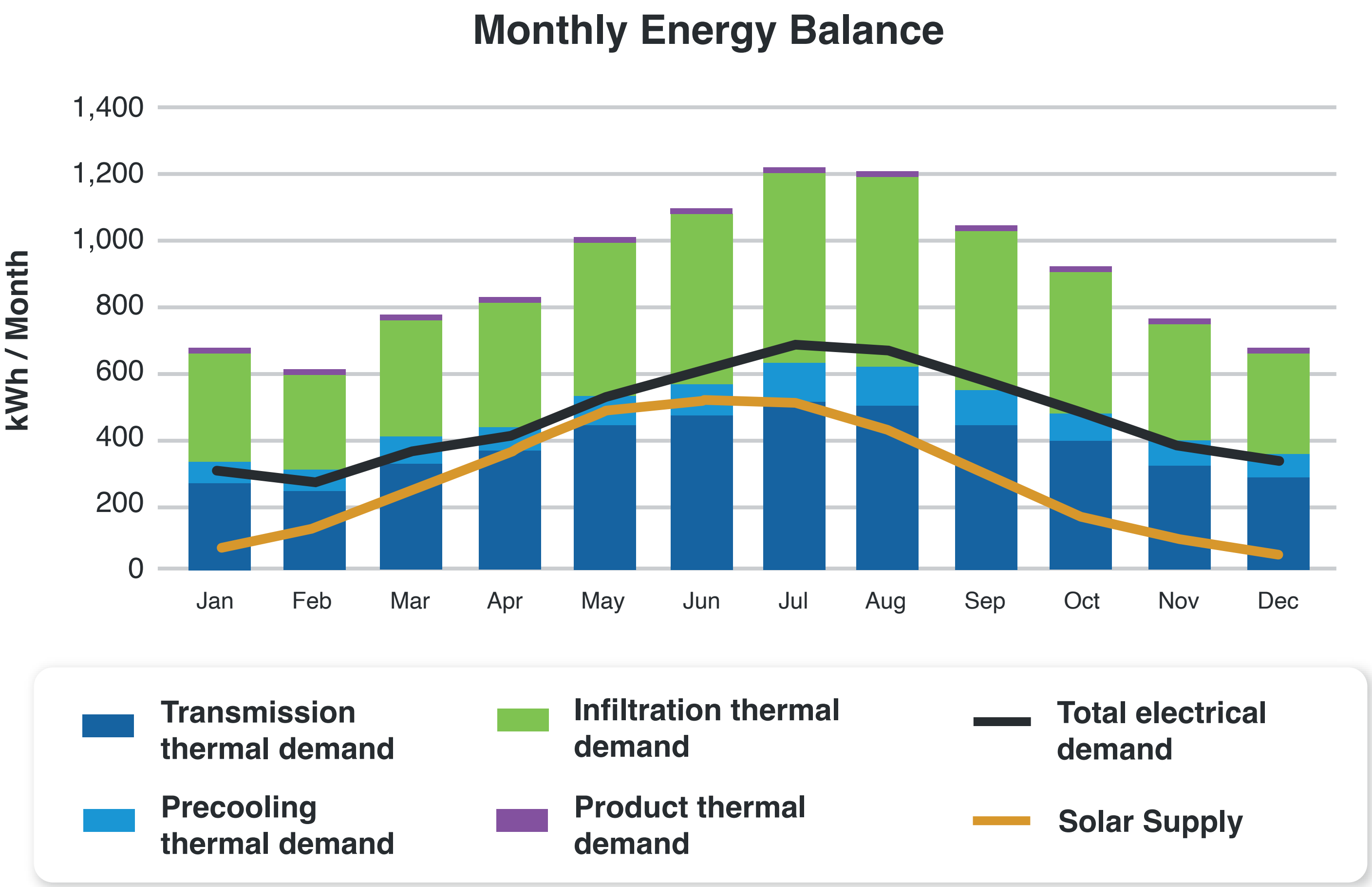
In this case we zoom in a day in February to accentuate the extremity of the low intensity case, when the thermal energy demand is the lowest, but the solar demand is also low compared to other months.





In the bottom graph we can observe that there is now a product thermal demand because the produce is fruit and vegetables (which produce respiration heat). This product load is proportional to the amount of produce in the trailer. Regarding the energy balance in the top graph, the battery simply acts as a buffer, providing energy when the electrical demand is higher than the solar supply, and then getting recharged from the solar panels to end the day fully charged. A smaller battery than 20 kWh would in theory be sufficient for this specific month and duty cycle.

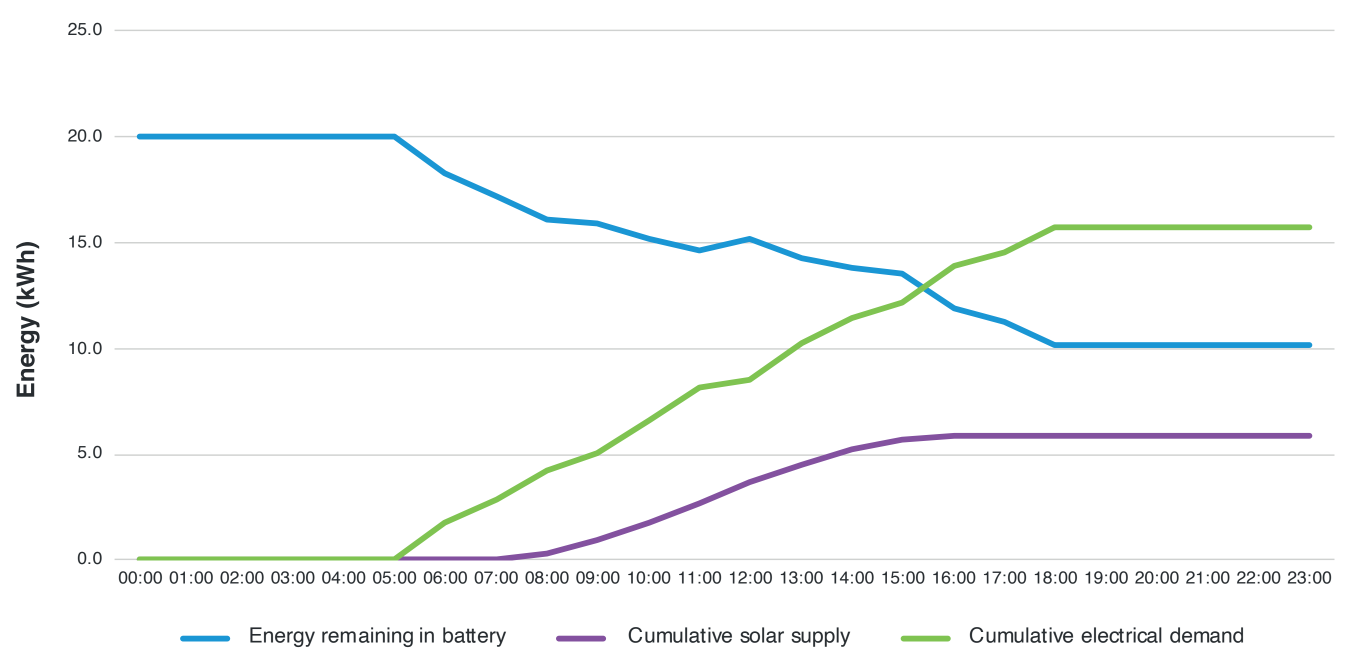
Medium Intensity Case

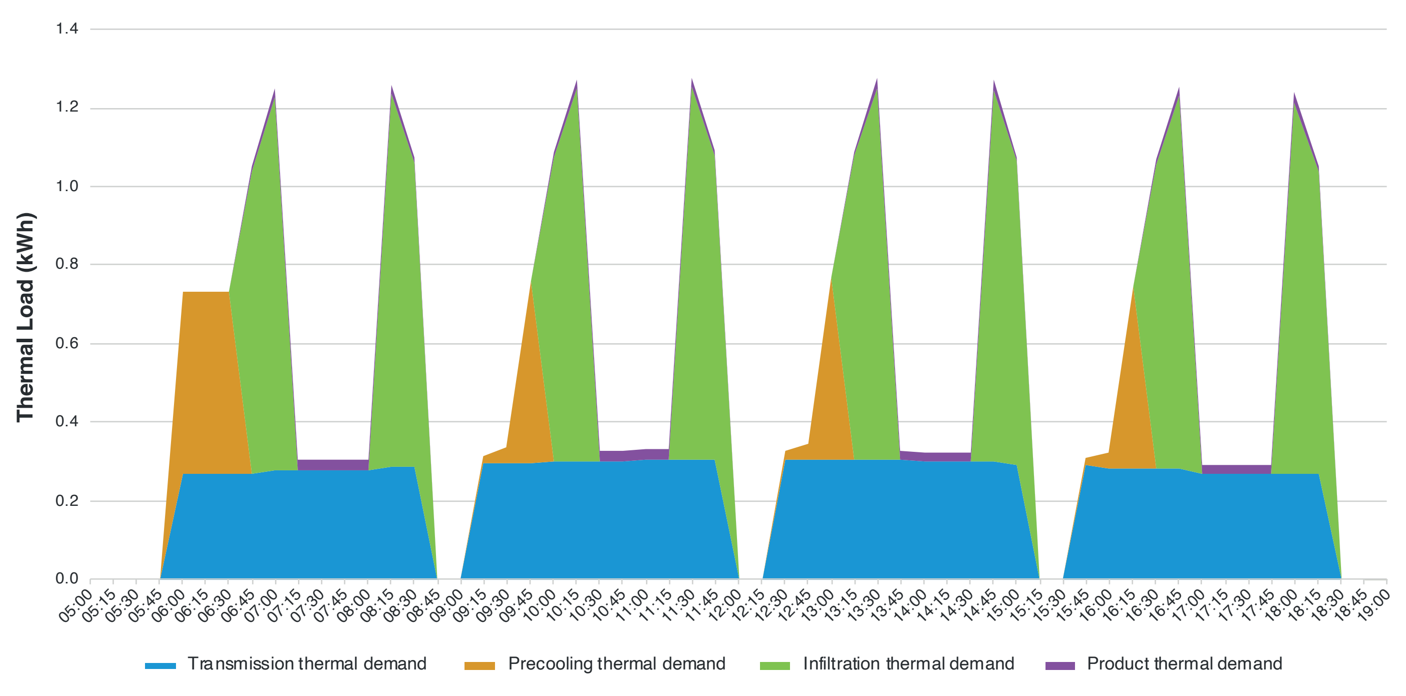


An average intensity case is a 13-hour, 4-deliveries/day operation with a triple compartment for frozen, chilled and ambient-temperature produce.

The grid charging requirement is small in spring, when the solar supply almost matches the electrical demand, but charging is still required during the rest of the year. However, the graph shows the good alignment between solar supply and energy demand all year long.

In this medium intensity case, we zoom in October, when both the energy demand and solar supply are average.

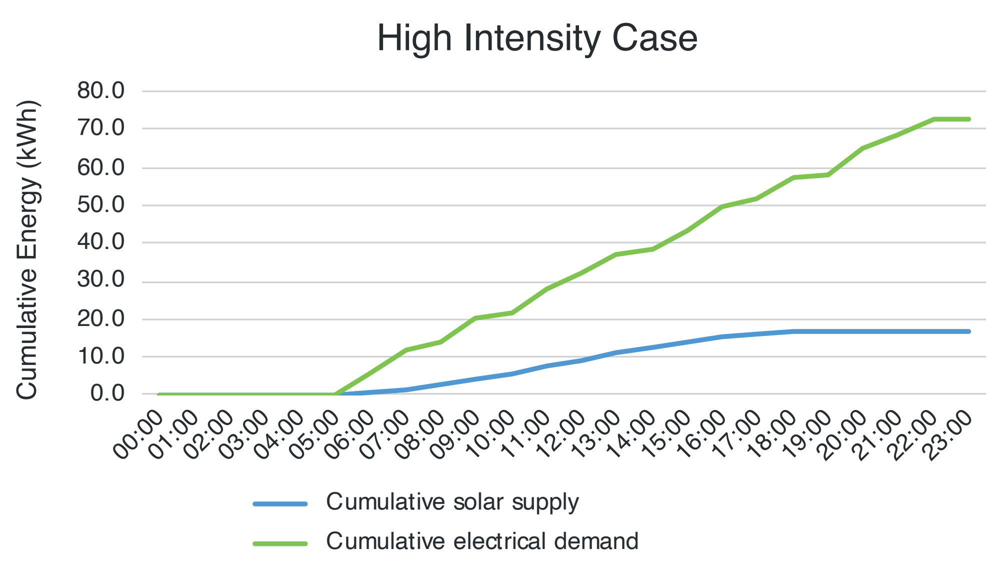


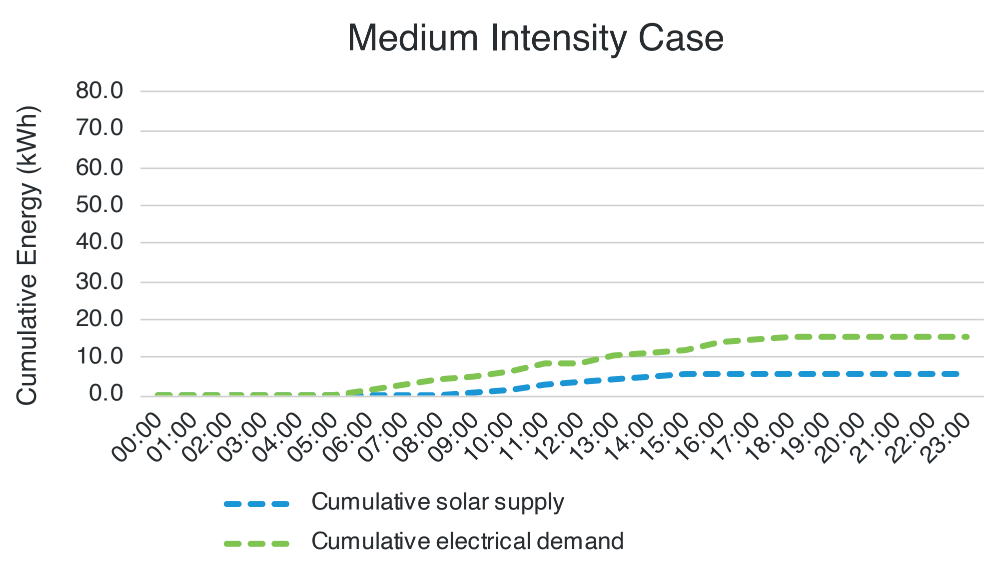


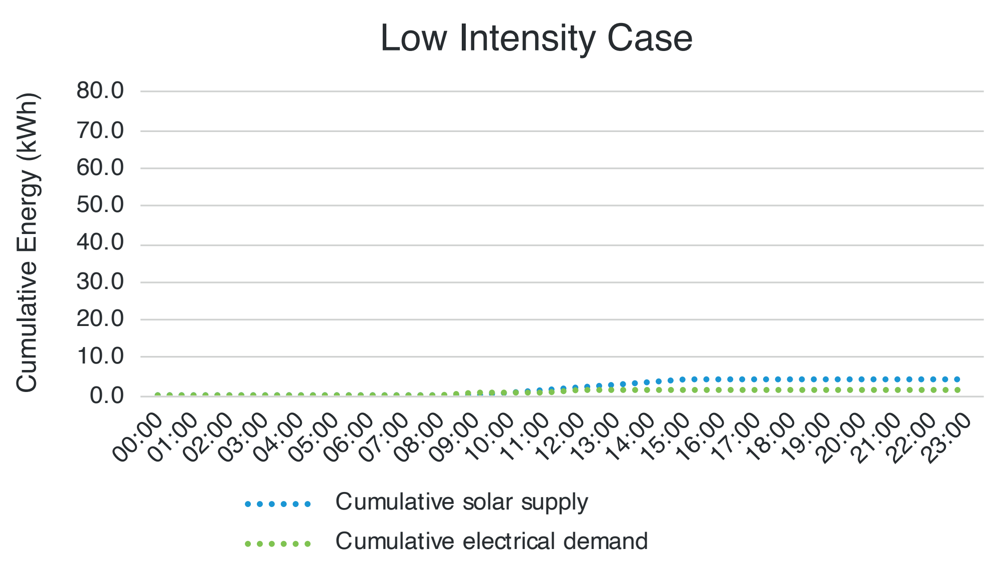
We can observe again the 4 cycles or deliveries with the variation in thermal demand types as previously explained. In this case, a 10-kWh battery would suffice to cover the demand, but due to contingency 20 kWh is the minimum allowed battery size.

Energy Modelling: Summary

The energy balance for the three intensity cases is shown below using the same scale in the vertical axis.

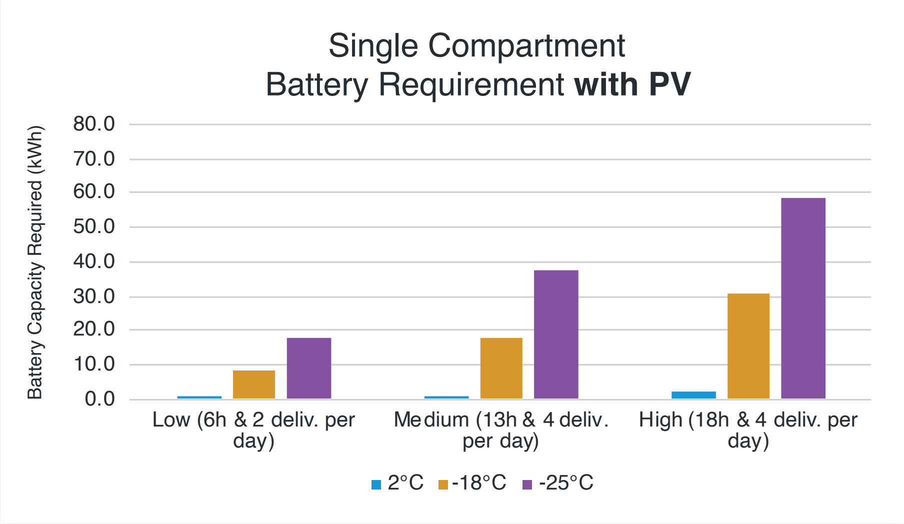


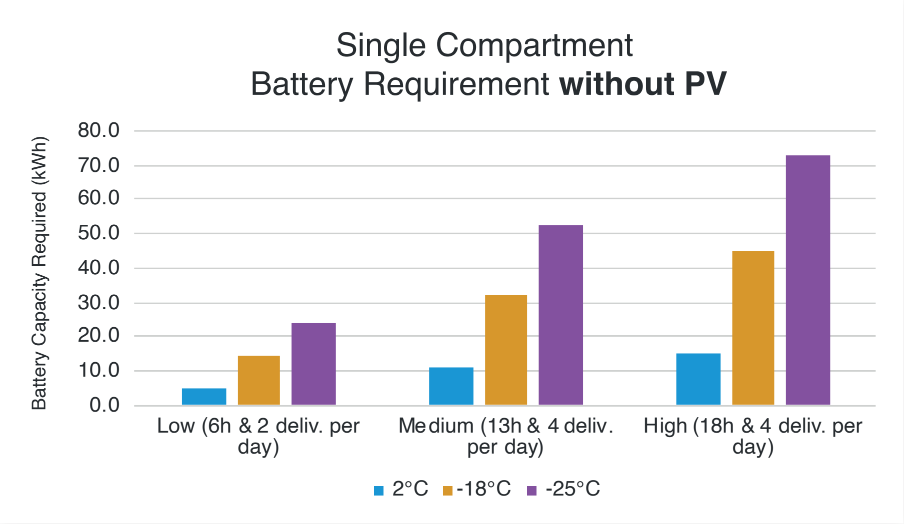


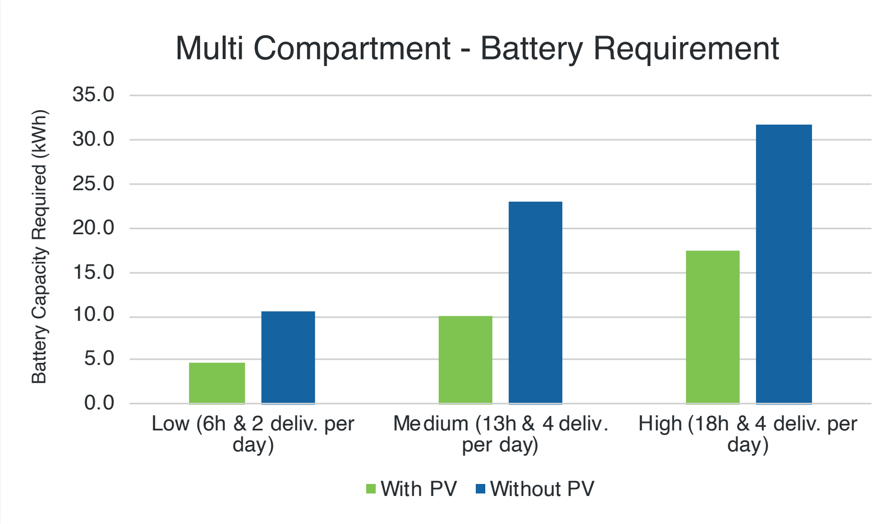


The large variation between the extreme high and low intensity cases justifies the need for an adaptative battery capacity, so that the system can cater for a range of customers and duty cycles. Even though the absolute energy levels are different between the high and medium intensity cases, the ratio of solar supply to refrigeration demand is similar in both cases.

To finalise the energy modelling review, we display below the battery capacity required for different temperatures and compartment configurations. We also show the battery capacity that would be required if there was not a solar PV on the trailer roof.


Single Compartment
Battery Requirement **with PV**


Single Compartment
Battery Requirement **without PV**


Multi Compartment - Battery Requirement

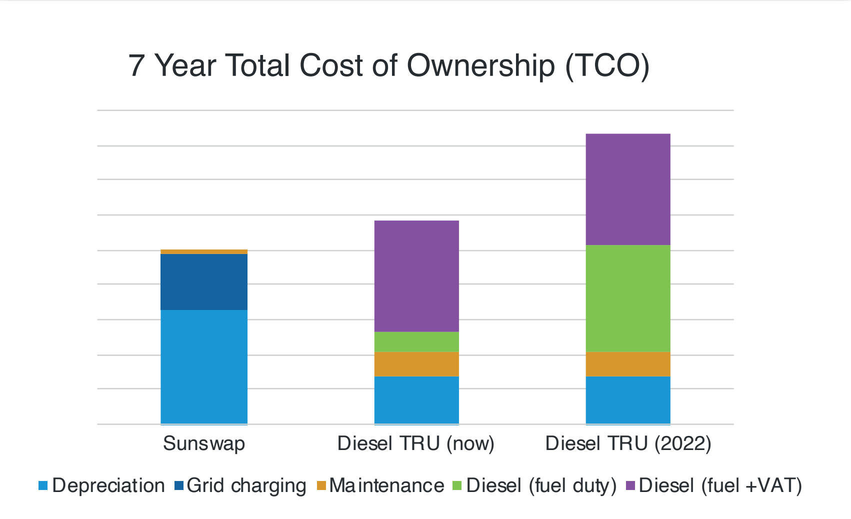
There is a large difference in battery requirement between the frozen and chilled temperatures, due to the higher COP at higher target temperatures and, obviously, due to the differential between ambient and target temperatures. **Thanks to the good alignment between the solar supply and the refrigeration demand, we can observe how the solar PV enables a reduced battery size.** In the single compartment case, this battery reduction is **between 3 and 15 kWh**, while in the multi-compartment case the reduction is **between 6 and 14 kWh**.

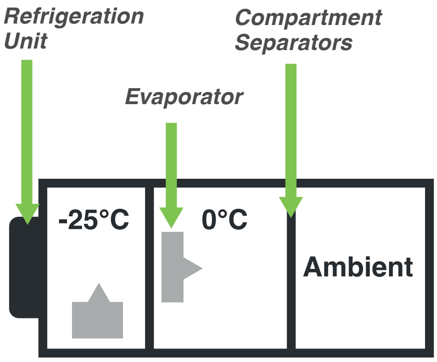
Economic Analysis

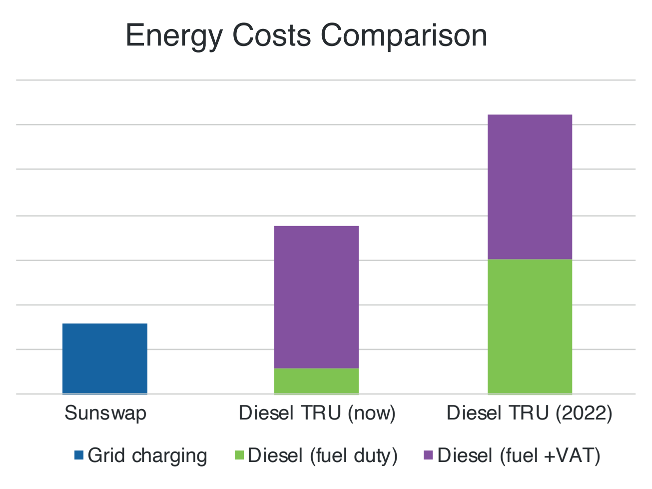
Cenex built a total cost of ownership (TCO) model from a fleet's perspective to compare the economic performance of Sunswap's transport refrigeration technology with a traditional diesel TRU over a 7-year period, which is the typical ownership of standard TRUs. The depreciation and maintenance costs have been obtained from industry feedback in the case of the diesel unit, and from Sunswap in the case of their system (including a peer-review to add impartiality to the assessment).

The diesel and electricity costs are average values for the last 12 months and come from standard industrial sources[1]. The UK Government announced in its 2020 budget the removal of the red diesel entitlement from April 2022 onwards, except for agricultural vehicles[2]. The red diesel fuel duty has historically been 11.14 pence per litre, compared to 57.95 pence per litre for regular diesel, but from 2022 the tax will be the same for both and so will be the final fuel price. Therefore, we have split the diesel cost into 'fuel duty' and 'fuel + VAT', and have analysed a diesel TRU now and from 2022 onwards.

The graphs below show a TCO and energy cost breakdown for a 7-year ownership period for the medium intensity case described previously. The vertical axis has been removed to preserve Sunswap's commercial confidentiality.



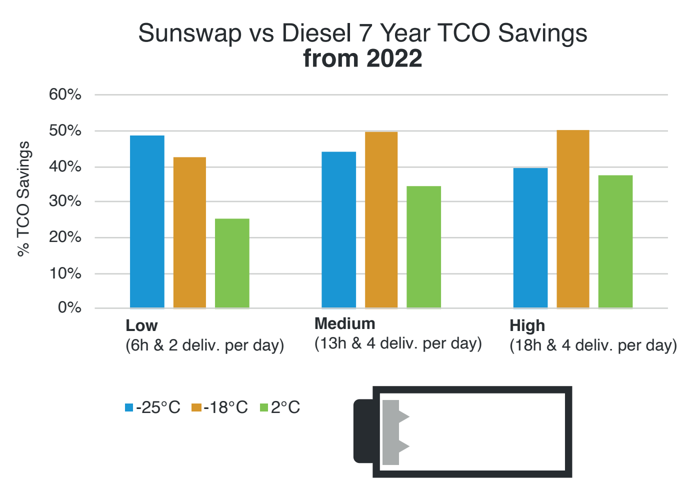


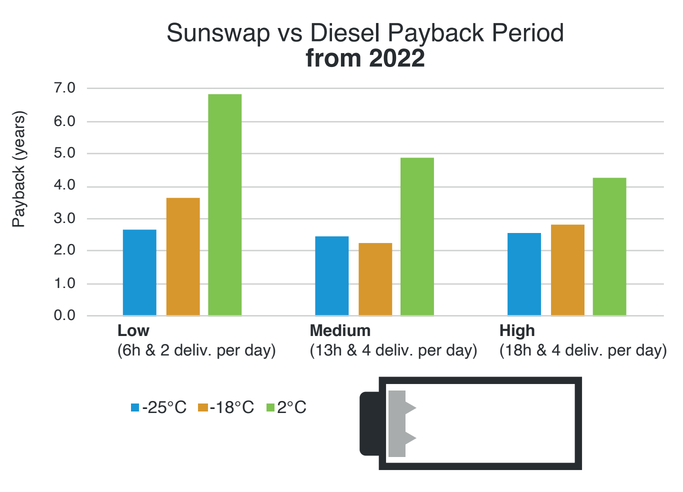


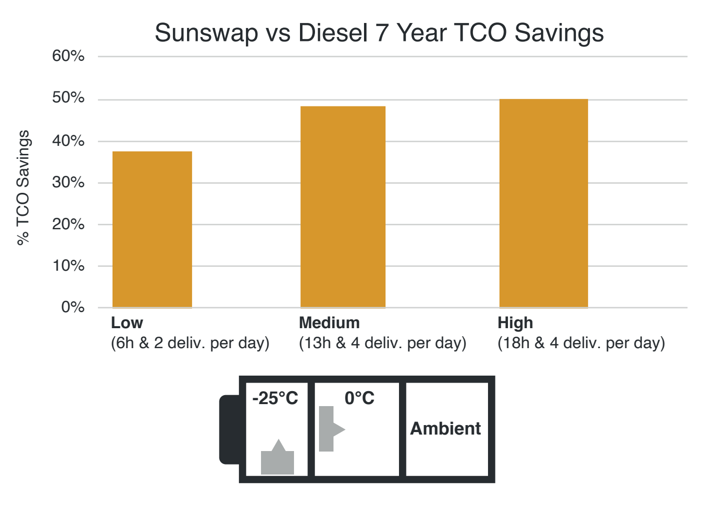
Compartments	**3**
Trailer Temperature	**-25°C, 0°C & ambient**
Duty Cycle Intensity	**Medium (13 h/day)**
No. Deliveries per Day	4
Diesel Equivalence	2,300 L/year

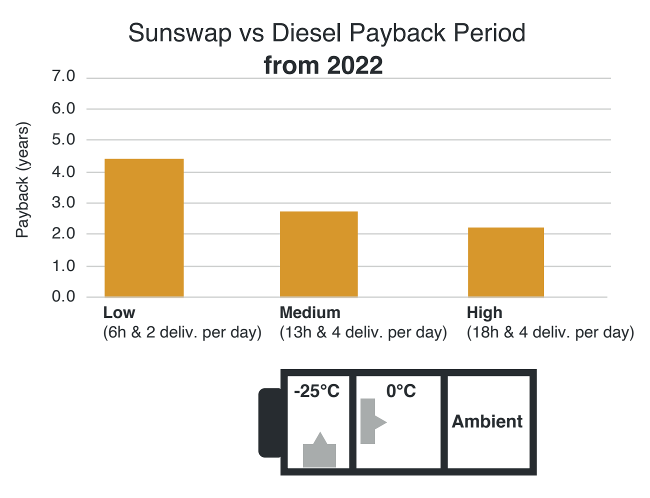
The Sunswap system has a higher capital cost than a diesel TRU, leading to a higher depreciation cost, because it is a novel and innovative technology. However, **the depreciation is recovered due to the lower maintenance and fuel costs compared to diesel.** The largest savings come from energy costs (fuel/electricity), hence why we have zoomed into these in the bottom graph. In this medium intensity case, the TCO savings are already 36% without the red diesel duty modification, and increase to 48% from 2022 onwards. The energy cost savings are 79% now and 87% from 2022.

The following graphs show the TCO savings over a 7-year ownership and payback periods (compared to diesel) for different trailer configurations and temperatures. Depending on duty cycle, the battery sizes can vary for each bar below, because battery size has an impact on TCO. Note that the information is given for a system operating from April 2022 onwards (red diesel tax increase) due to its proximity in time.









With lower temperatures and more intense duty cycles, a larger proportion of costs belong to fuel/energy. As the biggest savings from the Sunswap system come from fuel/energy costs, the overall trend is that more demanding duty cycles lead to higher TCO savings and lower payback periods. However, there is an exception to this trend with the -25°C target temperature, as this would require additional battery capacity that affects the cost performance.

The 7-year TCO savings range between 25 and 50%, while the payback period ranges between 6.8 and 2.3 years. Finally, having the solar PV reduces TCO by up to 22% compared to a Sunswap system without PV, due to the reduced battery capacity required and smaller amount of electricity to be charged from the grid.

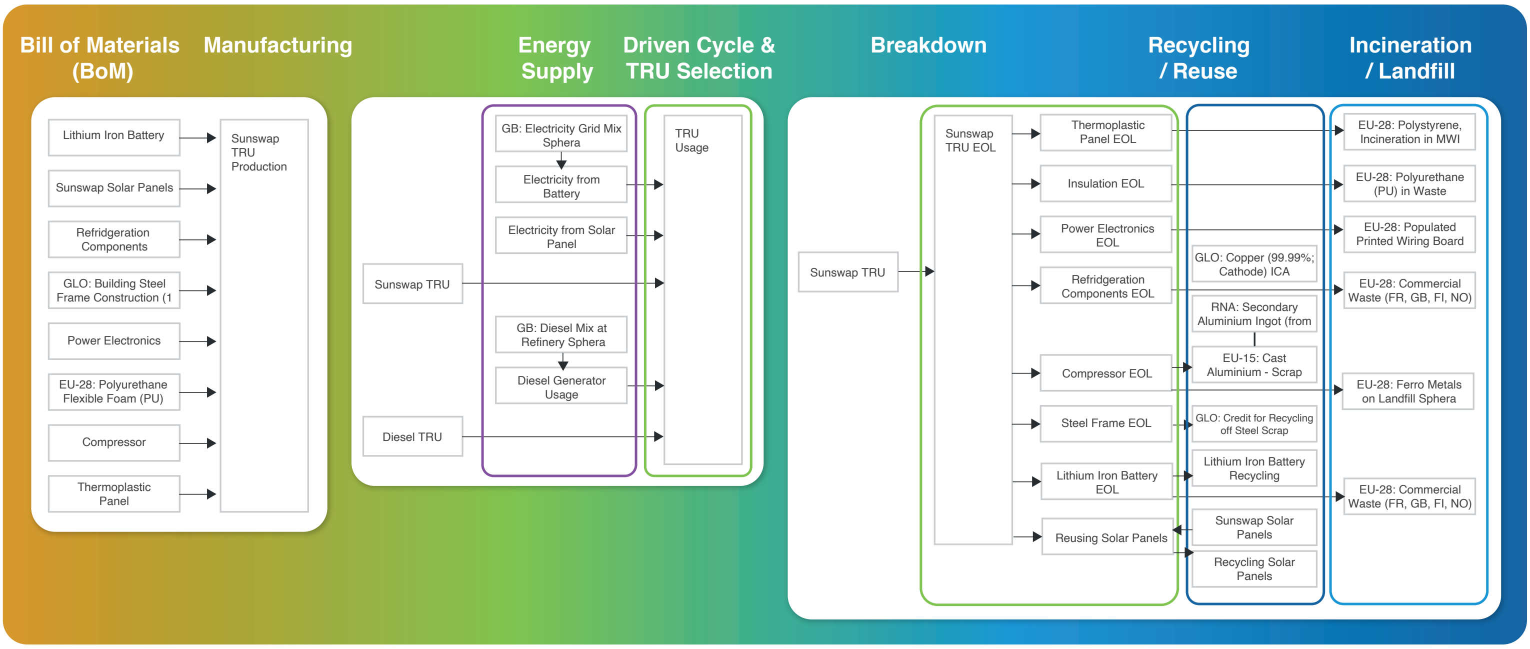
Life Cycle Assessment (LCA)

Life Cycle Assessment is a technique to analyse the environmental impact of the entire life cycle of a product, from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end of life treatment and final disposal[3].

We performed this analysis using specialised software[4] to compare the Sunswap system with a standard modern diesel TRU. The scope was restricted to the refrigeration systems and did not include any other components of the vehicles such as the trailer or tractor unit. There are some components that are common to both systems, such as the compressor, evaporator, frames or pipework, while others are different such as the power units and sources (diesel auxiliary engine and associated parts versus solar panels, batteries and power electronics).

The diagram below shows the top-level structure of the LCA model, where each of the grey boxes contain lower levels of the model.

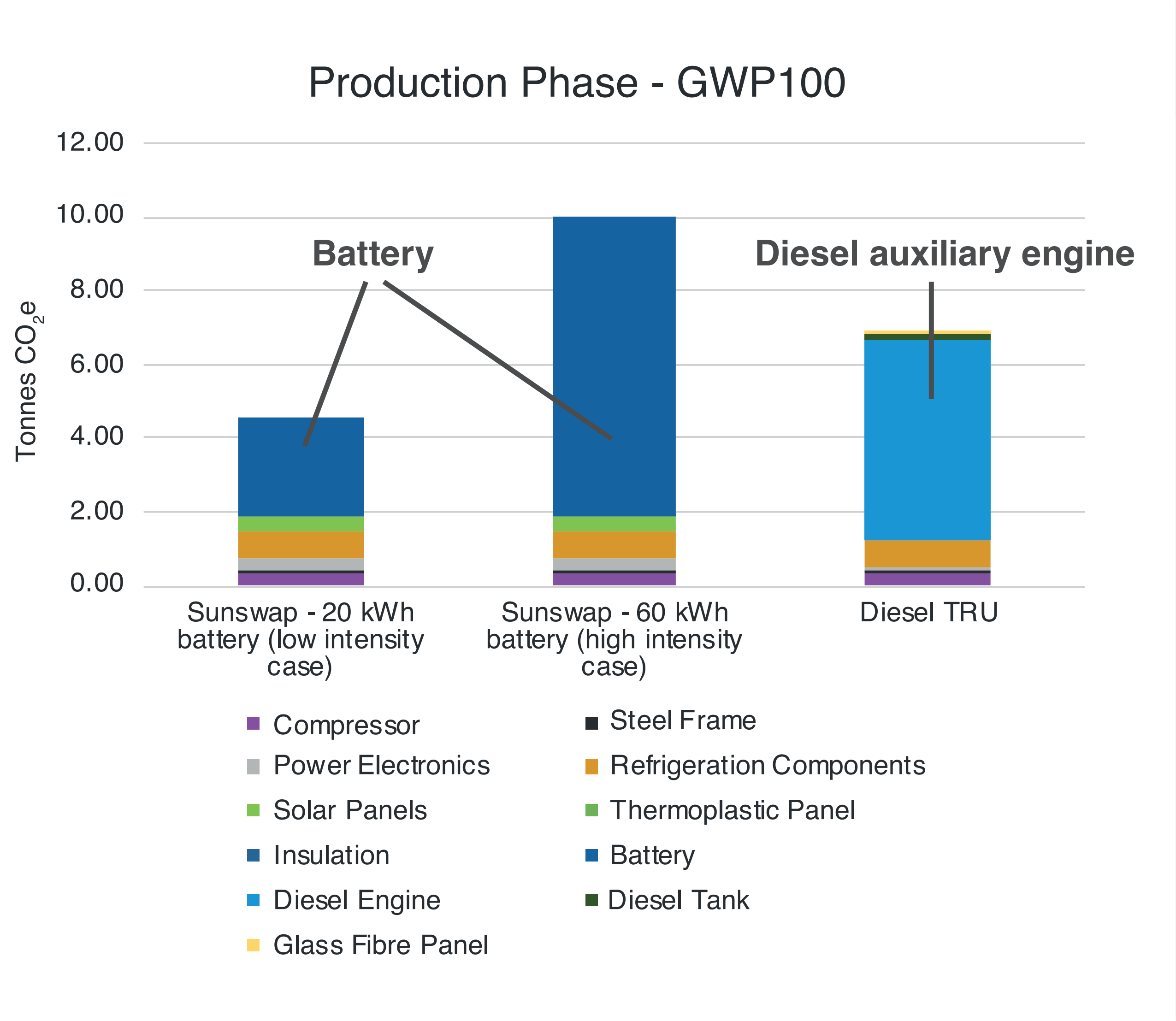
LCA Modelling



Production Phase

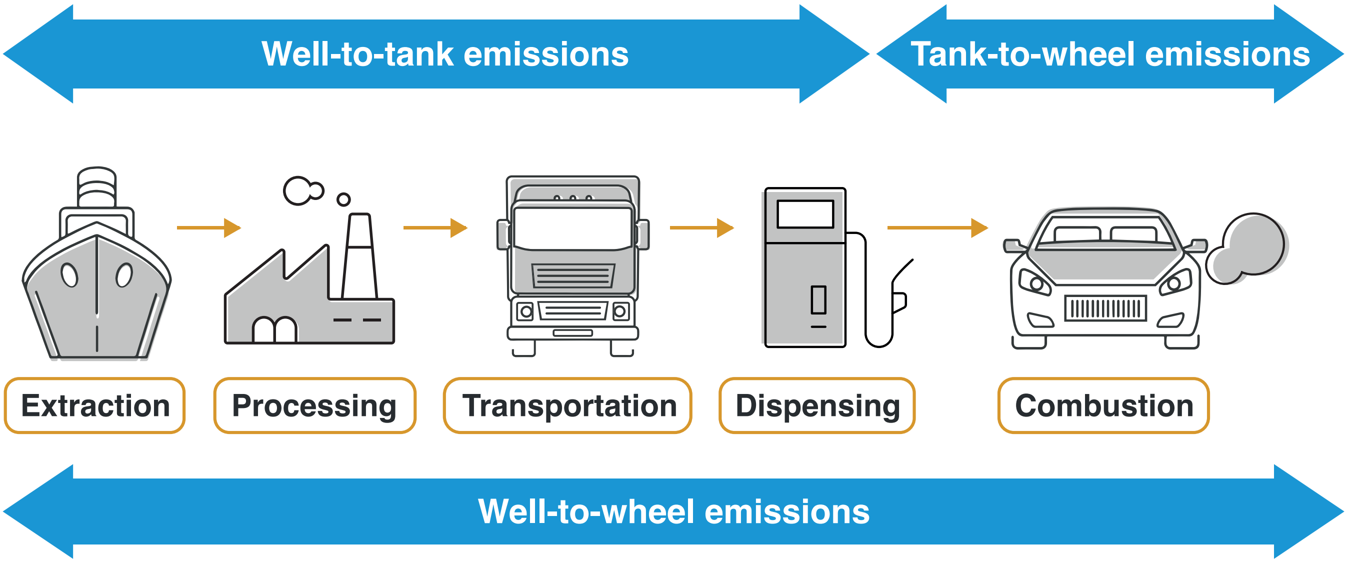
The raw material acquisition and production phases take into account the environmental impact of extracting the raw materials, transporting them to factories, manufacturing them into components, and finally assembling them to create the final product. In order to model these phases, we have used Sunswap's bill of materials for their system and literature research for the diesel comparator. The LCA software holds a vast library of data with the environmental impact from obtaining materials and producing components. Where materials or components were not available in the software, we have sourced them from literature.

The global warming potential over 100 years (GWP100) is the most popular LCA impact category and is defined as the heat absorbed by any greenhouse gas in the atmosphere, as a multiple of the heat that would be absorbed by the same mass of carbon dioxide. The graph below shows the modelled GWP100 of a diesel TRU and two Sunswap systems, one for a small battery requirement of 20 kWh (enough for the low intensity case presented previously), and one for a large battery of 60 kWh (required for the high intensity case).



The battery and diesel auxiliary engine have the largest production impact for Sunswap and diesel TRUs, respectively. In the Sunswap system, the battery accounts for 59 to 81% of the production impact, depending on duty cycle and hence battery size requirement. In the diesel TRU, the diesel auxiliary engine accounts for 79% of the production impact. **While the Sunswap system with a 20- kWh battery provides production GWP100 savings of 34%, a 60-kWh system would cause an increase of 45%.**

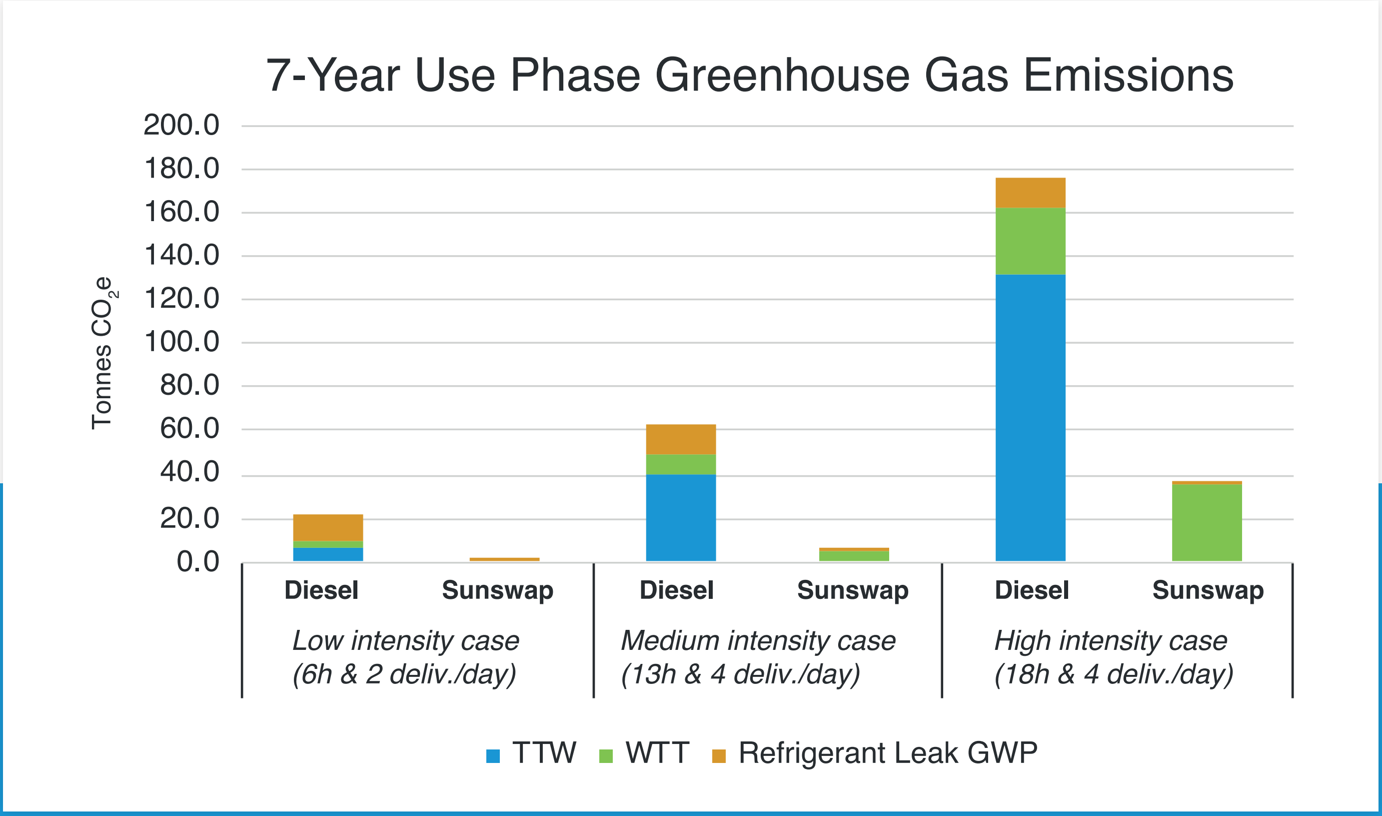
Use Phase


Sources of well-to-wheel emissions

In the diesel TRU, the use phase accounts for the emissions from the extraction, refinement, transportation and supply of the fuel (well-to-tank or WTT emission), and from the fuel combustion (tank-to-wheel or TTW emissions). Together they add up to the well-to-wheel (WTW) emissions, that consider the full life cycle of the fuel. In the Sunswap system, the use phase accounts for the emissions from the generation, transmission and distribution of the electricity (well-to-tank, WTT).

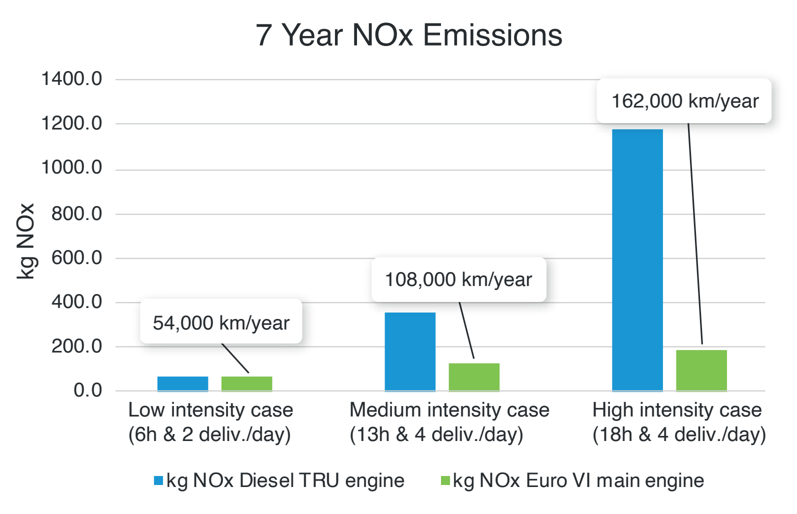
Both diesel and Sunswap systems also have emissions associated to the leakage of refrigerant, which is typically between 5 and 25% per year[5] (we have assumed a mid-range value of 15% for both systems). A refrigerant fluid is used within the refrigeration system in a closed loop to extract the heat from the produce to the ambient, although inevitably part of it leaks out to the atmosphere. Unfortunately, refrigerants can have very high GWP100 values: diesel TRUs have traditionally used refrigerants with a GWP of 3,900. However, from 2020 new cooling and refrigeration equipment cannot use refrigerants with GWPs higher than 2,499. For the diesel unit we have assumed a 2,140 GWP refrigerant as this is the common practice in new diesel units, whereas Sunswap are designing their system to use a novel refrigerant with a GWP of just 239. Diesel TRUs cannot be easily re- purposed to accept this lower GWP refrigerant as this would require a significant re-design of traditional diesel TRU units.

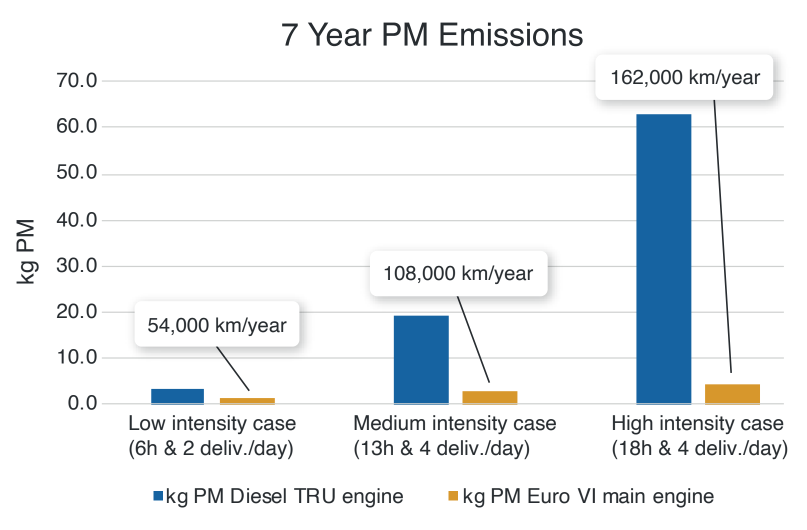
The following graph shows the use phase greenhouse gas (GHG) or GWP emissions for all three intensity cases for both Sunswap and diesel units. The UK electricity grid mix has been assumed in these calculations, but fleets that have access to on-site renewable energy generation can further reduce their electric TRU emissions.



The emission savings range between 79 and 93% depending on the intensity case. The largest proportion of savings originate from the lack of TTW emissions in the Sunswap system, although the savings available from the lower GWP refrigerant are also significant (89% less in the Sunswap unit compared to diesel).

The use phase air quality emissions, nitrogen oxides (NOx) and particulate matter (PM), only occur in the diesel TRU. We have calculated these emissions using the latest non-road mobile machinery (NRMM) stage V emission standards for diesel units with a power less than 19 kW (most diesel TRUs have this power). These standards were only enforced for new diesel TRUs bought from 2019, which means that most diesel units currently on the road do not have to comply with these standards. For context and comparison, we have also added the emissions from a Euro VI diesel tractor unit, which is a standard introduced in 2013. The annual distances represent what is driven in a year between distribution centre and supermarkets/shops for each of the duty cycles, hence why the high intensity cycle has a much higher mileage than the low intensity one.

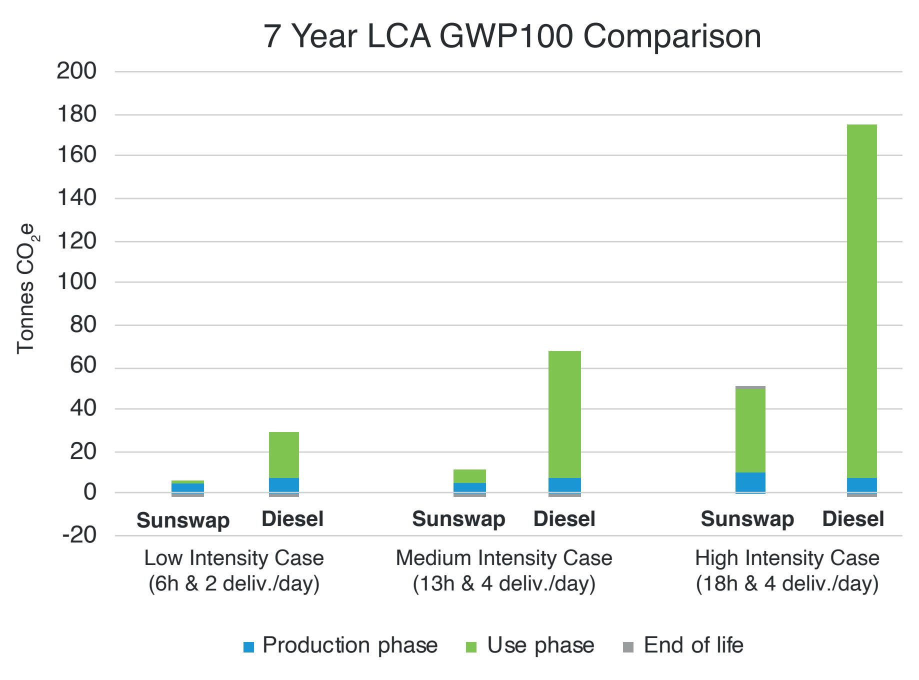


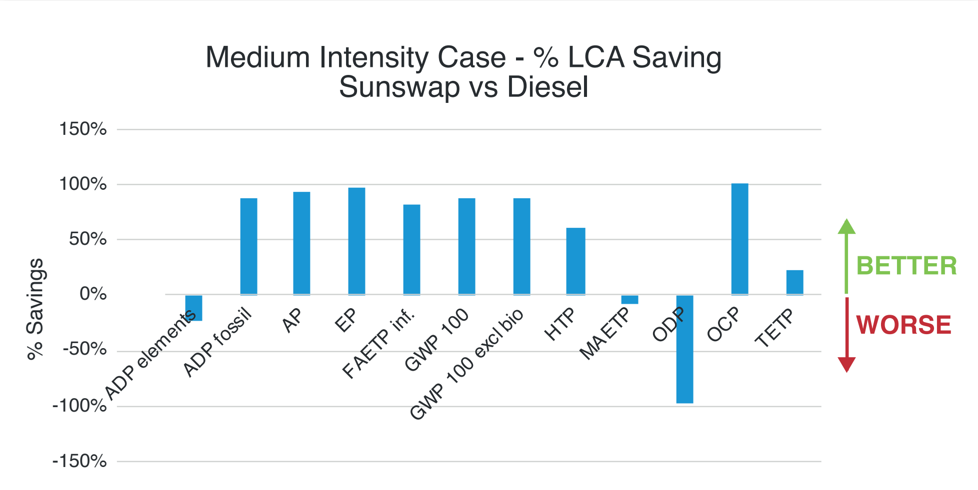


The total NOx emissions from the TRU engine are 1 to 6 times higher than the emissions from driving of the truck's main engine, while PM emissions range between 2 to 14 times higher. This happens because Euro VI engine emission standards are far more rigorous than NRMM stage V standards. While the Euro VI engine emissions are directly proportional to the annual distance or driving hours per day, the TRU engine emissions not only depend on the number of operational hours but also on the trailer target temperature (2°C in the low intensity case versus -25°C in the high intensity case).

Note that these are conservative results, as diesel TRUs bought earlier than 2019 will even have worse air quality emissions than the ones shown in the graphs.

The graphs below show the whole life environmental impact results (i.e., production, use and end of life phases) for Sunswap and diesel TRUs under a variety of intensity scenarios. The first graph shows only the GWP100 results, while the second graph shows the savings of the Sunswap system compared to a diesel unit for the most relevant LCA categories.





The LCA results are driven by the use phase, although the production phase has more relevance in the low intensity cases due to the relatively lower energy use in those. We have not included the end of life results because, as per the LCA results, their impact is negligible compared to the production and use phases. **The GWP100 savings range between 77 and 93%** depending on duty cycle and refrigeration temperature. Moreover, there are major savings in most LCA impact categories. There are just three categories that have worse impact compared to diesel, and this is due to battery production, which is an energy intensive process and one that uses exotic materials in its manufacturing.

Acronyms are explained in [6]

Study Conclusions

Energy modelling:

- Transmission and infiltration losses dominate thermal demand.
- Seasonal and daily variance in demand is well aligned with solar supply
- Therefore, solar PV enables reduction in battery size required by 6 - 15 kWh

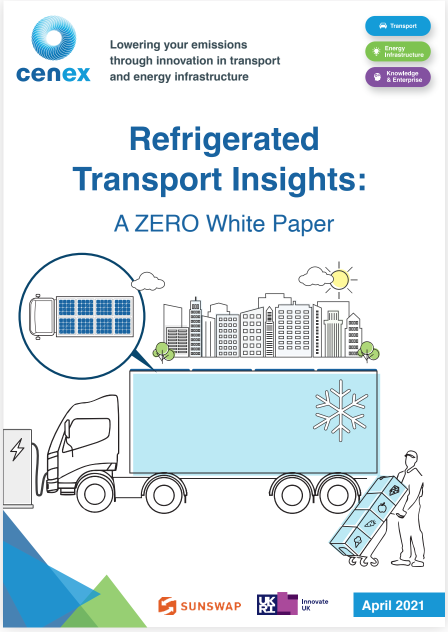
Economic analysis:

- Higher capital expenditure of the Sunswap system is recovered due to its lower operating expenditure compared to diesel
- From 2022, TCO savings will be between 20 and 50% compared to diesel
- Multi-compartment operation from 2022 achieves payback in 2 to 4 years compared to diesel

Life cycle assessment (LCA):

- Reduction of 77 to 93% in LCA climate change impact, large savings in most LCA impact categories
- Production phase: -34 to +45% difference in climate change impact (depending on battery size)
- Use phase: reduction of 79 to 93% in GHG WTW emissions, 100% reduction in NOx and PM

Further reading


cenex

Lowering your emissions
through innovation in transport
and energy infrastructure

Transport
Energy Infrastructure
Knowledge & Enterprise

Refrigerated Transport Insights:

A ZERO White Paper

SUNSWAP
UKRI Innovate UK

April 2021

About Cenex & Sunswap

Independent non-profit experts in low emission transport research and consultancy headquartered in Loughborough (UK), with offices in Edinburgh, Amsterdam and South Korea. We accelerate the shift to low emission transport and energy solutions by delivering projects that support innovation and market development.

info@cenex.co.uk

Cleantech startup on a mission to decarbonise the cold chain through the development of zero-emission transport refrigeration technology. Our products use solar power and adaptive battery capacity to provide a clean and cost-competitive solution.

info@sunswap.co.uk

References

[1] Diesel price from the AA, electricity price for non-domestic users from UK Gov.

[2] Reforms to the tax treatments of red diesel and other rebated fuels: consultation. HM Treasury, July 2020

[3] ISO 14040:2006 LCA, principles and framework

[4] Software: GaBi Professional

[5] US Environmental Protection Agency (EPA, link), Rai and Tassou (Brunel University, link), PhD Thesis (Brunel University, link)

[6] Abiotic Depletion (ADP elements), Abiotic Depletion (ADP fossil), Acidification Potential (AP), Eutrophication Potential (EP), Freshwater Aquatic Ecotoxicity Potential (FAETP inf.), Global Warming Potential (GWP 100 years), Global Warming Potential (GWP 100 years), excl. biogenic carbon, Human Toxicity Potential (HTP inf.), Marine Aquatic Ecotoxicity Pot. (MAETP inf.), Ozone Layer Depletion Potential (ODP, steady state), Ozone Creation Potential (OCP), Terrestrial Ecotoxicity Potential (TETP inf.).

You can find out more about our research projects, along with downloading a range of free, public reports, from our website:

www.cenex.co.uk

Cenex
Holywell Building
Holywell Park
Ashby Road
Loughborough
Leicestershire
LE11 3UZ

Tel: 01509 642 500
Email: info@cenex.co.uk
Website: www.cenex.co.uk