Potential carbon sequestration at Malmö Airport by use of extensive green roof.

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Abstract

Huge amounts of greenhouse gases continuously released into the atmosphere is of large global concern. Carbon dioxide makes up a large part of released greenhouse gases. Especially the aircraft industry, which is experiencing a steady annual increase as air travel grows in popularity. This business sees 72% of all its combustion products in aircraft exhausts to be carbon dioxide. Swedavia, a company striving to be a leader in sustainable airports has therefore set a neutral carbon dioxide goal regarding their own activities by the end of 2020. Swedavia therefore intends to sequester as much carbon as they release from their vehicles and back-up diesel engines, minus work/related travelling. This paper investigates possibilities of using an extensive green roof at Malmö Airport to reduce carbon emission to neutral for all major sources related to airport activity, not just Swedavia’s own emissions. Conclusion on project feasibility are based on previous carbon sequestration research, CO_2 emissions of Malmö Airport and roofed area available for an extensive green roof installation. By using the amount of carbon capable of being sequestered per m2 of extensive green roofs, it was possible to calculate a total area of green roof which would need to be installed at Malmö Airport. Results proved to be impossible to apply practically and using solely green roofs to reach carbon neutrality by the end of 2020 is therefore not feasible.

Abbreviations

CO_2- carbon dioxide
GHG- Greenhouse Gases
PM- Particulate Matter
C- Carbon
LTO- Landing Takeoff
GPU- Ground Power Unit
APU- Auxiliary Power Unit
VOc- Volatile compounds
NOx- Nitrogen oxides

Relevant terminology

Extensive green roofs
Carbon Sequestration
Carbon Dioxide
Airport

1. Introduction

1.1. Purpose of research

This paper aims to investigate if an extensive green roof installation at Malmö Airport can bring CO_2 emissions of Malmö Airport to void, allowing Swedavia to not only achieve their 2020 goal of CO_2 neutrality regarding release for own emissions, but also all major emissions related to aircraft activities.

1.1.1.) Research question

Could the installation of an extensive green roof at Malmö Airport result in neutral CO_2 emissions from all major sources related to Malmö Airport down to by the end of 2020?

1.1.2.) Delimitations

As seen in *table 1*, extensive sedum roofs provide more benefits than intensive ones. Therefore, this paper will only investigate carbon sequestration for extensive green roofs. This can prove to be a limiting factor as only one species of plants, the *sedum* plants are typically used, but as more widely researched on, this type of roof possesses more data and research availability. For area estimations regarding roofs found on constructions at Malmö Airport, building area was assumed to be an equal representation of roofed area. Green roof requires extra strength in roof structures to support any additional weight from substrates, it is therefore likely that any protruding roof parts from buildings might not be strong enough to support an extensive green roof installation, without expensive structure strengthening *(Hall, Gail, et.al.,2014)*.

Another delimitation set in this paper is the three-year time span allocated for carbon sequestration for a potential extensive green roof at Malmö Airport. As CO_2 emissions are expected to increase after 2020, it is important to consider this factor regarding future emissions over time.

1.2.1 Background Information

1.2.2.) Air pollution

In 2012 the World Health Organisation (WHO) estimated that around 3.7 million premature deaths were linked to outdoor air pollution. Although considered a basic human right, this estimation shows that unpolluted air is still unavailable to many. Pollution issues regarding clean air have therefore led diverse organisation, such as WHO, the European Union and the Environmental Protection Agency, to set limits for atmospheric pollution concentrations (*Tallis, Matthew J., et al., 2015*).

Absorbed solar energy and thermal radiation emitted back to space, through earth and atmosphere, tend to be in equilibrium. Alteration of this balance is called radiative forcing, and it is believed radiative forcing has possibilities of causing climate change (*Shine K.P, et.al, 1996*). This phenomenon usually occurs when greenhouse gases, such as CO_2 are emitted. Carbon Dioxide (CO_2) is considered to be the greenhouse gases (GHG) and as such it plays a primary role in Earth's climate change. In turn, these changes causing widespread global concern (*Masiol, Mauro, and Roy M. Harrison, 2014*). As can be seen in *diagram 1*, CO_2 effects are not simply limited to local areas, rather the reaction affecting earth's climate on a global scale. Excess of CO_2 is stored in the ocean biosphere, in turn causing ocean acidification (*Raven, John, et.al., 2005*).

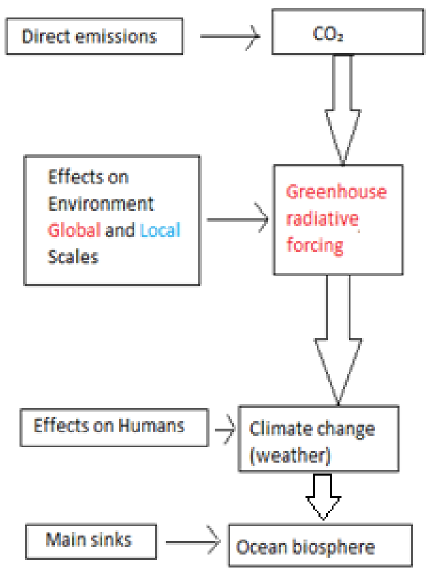

Diagram.1, based off a figure from *Masiol, 2014,* it shows environmental and human effects caused by CO_2 release, as well as CO_2's main sink (*Masiol, Mauro, Roy M. Harrison, 2014).*

A large amount of today’s environmental and political debates are linked to CO_2 release. They have resulted in the creation of many limits and guidelines. The Kyoto protocol in 1977 *(UNFCCC, 2008)*, the Doha amendment in 2012 *(United Nations,2014)* and the Paris Agreement in 2016 *(United Nations, 2017)* are some of these major international collaborations, created with the purpose of addressing CO_2 emission regulations.

1.2.3.) Aviation

In 2012 the World Health Organisation (WHO) estimated that around 3.7 million premature deaths were linked to outdoor air pollution. Although considered a basic human right, this estimation shows that unpolluted air is still unavailable to many. Pollution issues regarding clean air have therefore led diverse organisation, such as WHO, the European Union and the Environmental Protection Agency, to set limits for atmospheric pollution concentrations, such as CO_2 (*Tallis, Matthew J., et al., 2015*).

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1.2.4.) Swedavia and Malmö Airport

Swedavia is a Swedish state owned company, aiming to become a role model within sustainable development. Already world leading when it comes to creating sustainable airports, they are currently responsible for ten airports in Sweden *(Swedavia, 2017).* These can be seen in *figure 2 below*

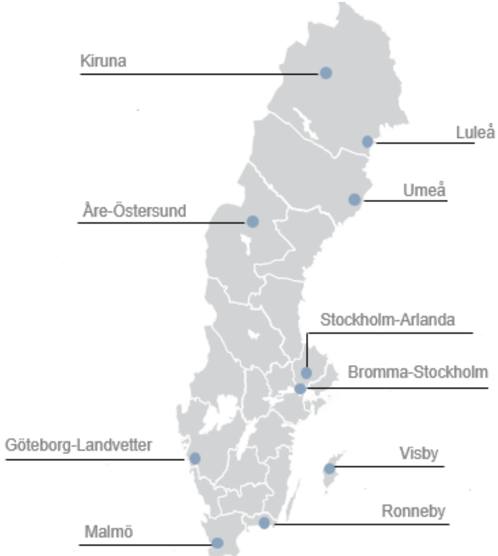


Figure 2, map of Swede with all ten airports managed by Swedavia (*Jonasson, Maria, 2017*).

Swedavia works with Airport Carbon Accreditation (ACA), a program created to manage and reduce CO_2 emissions at airports (*Airport Carbon Accreditation, 2009*). Aiming to sequester as much carbon as they release, Swedavia intends to bring CO_2 emissions from their vehicles and back-up diesel engines, minus work/related travelling, down to neutral by the end of 2020

Malmö Airport is an airport constructed in 1972. In 2016 it was used by 2.2 million travellers. It is very close to achieving neutral CO_2 emission goal for Swedavia's own emissions, through strategies such as use of green fuel and improved airport engines, which can be seen in *fig. 1 below (Swedavia, 2017).* However, there is still a large amount of carbon dioxide released through aircraft related activities.

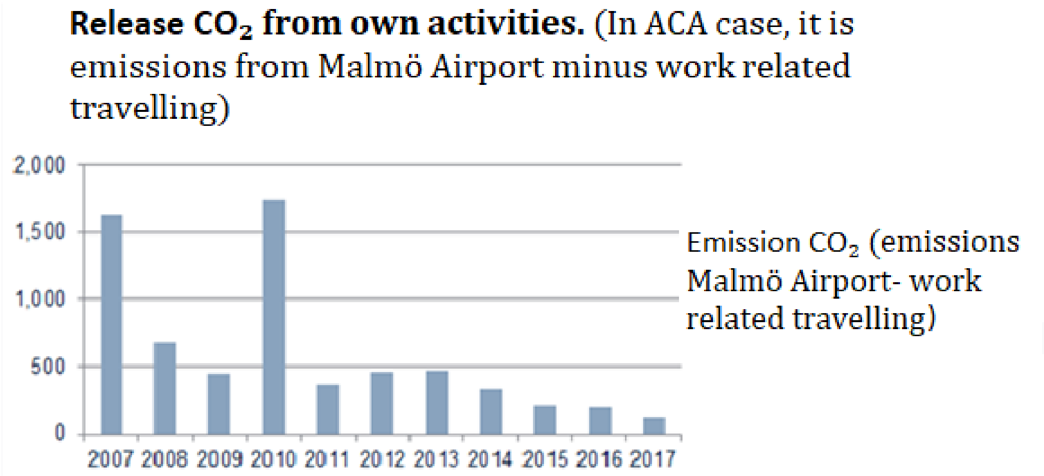


Fig 1. Release of CO_2 from Swedavia's own business over the years (*Jonasson, Maria, 2017*).

1.2.5.) Landing Takeoff , Ground Power Unit and Auxiliary Power Unit

Within the aircraft sector, main activities responsible for CO_2 emissions at airports are landing takeoff (LTO), Auxiliary Power Unit (APU) and Ground Power Unit (GPU) activities. LTO emissions are, much like its name suggests, measured at landing and takeoff of airplanes. They refer to all aircraft operations carried out below 914 meters of field elevation. This height corresponds to the atmospheric mixing height, or lower part of the troposphere, where emitted pollutants rapidly mix at ground level *(Masiol, Mauro, Roy M. Harrison, 2014).*

APU's on the other hand, are small gas turbine engines used primarily during aircraft ground operation. Providing electricity, compressed air, and/or shaft power for main engine start and other aircraft systems, they also provide backup electric power during in-flight operations. Acting as a supplementary power source, APU's are later used to start main propulsion engines and provide pressurised air for the environmental control systems *(Pratt and Whitney, 2017)*. APU's therefore enable aircraft consumers to operate autonomously, avoiding reliance on ground support equipment, such as electrical power unit/battery/generator, external air-conditioning unit, or high pressure air unit/batteries *(Tudosie, Alexandru-Nicolae., 2016).* Lastly, GPU's are generators supplying electricity to static aircrafts, before engines have been started. Thus they enable functioning of lightning and air-condition *(Beaver, Allan, 2012).*

1.2.6.) Green Roofs

Green infrastructure, more specifically green roofs, have become a popular method of minimising negative environmental effects. In urban areas, where around 30-60% of cities are made out of permeable areas *(Rowe, D. Bradley. 2010)*, they offer a myriad of benefits. Some examples include reduction of water runoff by 50-100%, absorption of sound waves, reduction of air pollution and longer longevity (45 years) than normal roofs (20 years). The latter is attributed to protection of rooftops from ultraviolet light and extreme temperature fluctuation offered by the vegetation, providing long term benefits *(Oberndorfer, Érica, et al., 2007).*

Studies have proven that around 85 kg of air pollutants can be removed annually by a hectare of green roof *(Chen, Chi-Feng, 2015).* Air pollutants such as PM, NOx and carbon dioxide can therefore be reduced by use of green roofs (*Li, W.C., and K.K.A Yeung, 2014)*. Although CO_2absorption rate for green roofs is higher than the emission rate, there is still a severe lack of experimental data *(Chen, Chi-Feng, 2015)* and research on CO_2-uptake by green roofs is poor *(Collazo-Ortega, Margarita, et.al, 2014).*

Originating in Germany around 1880, modern green roofs were originally used as means to make houses less flammable in the rapidly industrialising Germany *(Getter, Kristin L, D. Bradley Rowe, 2006)*. Today, the nation is considered a leader in green roof technology, with more than 10% of houses having installed some form of green roofs (*Bass, B. et.al. 2003).*

Not limited to urban dwellings, green roofs have been adopted by many international airports such as Frankfurt (Germany), Schiphol (Netherlands) and Kloten (Switzerland). Frankfurt international airport for example, has installed a 17 000 m² green roof. Aart Veerman, President of the International Green Roof Association and Commercial Director of Van der Tol b.v. has estimated the extensive green roof area at Schiphol to be around 13 330 m², and Kloten Airport has installed one of the largest green roof building sites in Switzerland *(Velazquez, Linda S, and Benjamin Taube, 2008).* Ecological, economical and aesthetic benefits of these installations have been noted, and are believed to mitigate some of the environmental consequences of airports and airlines. According to Robert Payne, spokesperson for Frankfurt Airport Services Worldwide, it has “proven to be remarkably heat-resistant and therefore helps to cool down the entire terminal building” *(Scott, Lewis, 2012)*.

Vegetation removes CO_2 by breaking down organic compounds with plant tissue and soil substrate *(Li, W.C., and K.K.A Yeung, 2014).* This in turn gives plants abilities to sequester carbon. Through photosynthesis of CO_2, carbon is bound into plants; soil substrate, root exudates and plant litter (*Rowe, D. Bradley, 2010).* Carbon binding ability for vegetation varies with seasons, also being affected by illuminance and temperature (*Chen, Chi-Feng, 2015).* As pollution deposited on vegetation generally follows a concentration gradient, vegetation closer to a pollution source therefore sequesters and bind more pollutants *(Tallis, Matthew J., et al, 2015).*

1.2.7.) Extensive and intensive green roofs

Most green roofs have similar construction components (*see Fig.2*). A root barrier to protect the roof from root damage, drainage layer for excess water to flow away, and a filter fabric that keeps pollution from clogging the drainage layer. An optional water retention can also be included. Most common types of green roofs are extensive and intensive green roofs, each with their benefits and disadvantages, see *table 1* below (*Getter, Kristin L, D. Bradley Rowe, 2006)*.

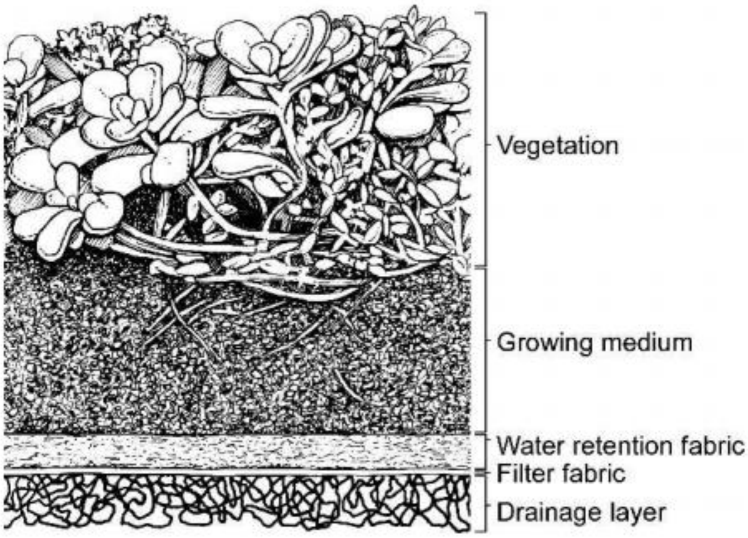


Fig. 2. shows a layout for a typical green roof installation, top to bottom. A vegetation layer is found on the surface, planted on a growing medium (often soil) and a drainage layer removes excess water *(Getter, Kristin L, Bradley Rowe, 2006).*

Table 1, benefits and disadvantages of extensive and intensive green roofs.

	Extensive *(Sedum)* Green Roofs	**Intensive Green Roofs**
Benefits	-Plants establish fast -Reproduce efficiently -Short heights of plants -Cushion forming-mat forming -Shallow roots that spread in longitude -Succulent leaves which can store water -Least expensive -Minimal maintenance	-Wider range of plants -More aesthetically pleasing
Disadvantages	-Limited range of plants due to shallow depth -Limited roof area available -Not best at CO_2 binding	-More expensive -More maintenance -Larger soil depth needed -Limited roof area available

The main disadvantage of extensive green roofs is their limited range of plants and lesser CO_2binding capacity (*Getter, Kristin L, D. Bradley Rowe, 2006)*. They are nonetheless a more advantageous option than intensive roofs in most other areas. As they are more commonly used, the study will only focus on extensive green roofs, due to lack of previous research and limited time availability.

Limitations in adequate vegetation for extensive green roofs, means that *sedum* species tend to be favoured (*Li, W.c., and K.k.a. Yeung, 2014*). These plants are resistant to long drought periods, high temperature and strong winds *(Collazo-Ortega, Margarita, Rosas Ulises, Reyes-Santiago Jerónimo, 2017),* making them very robust. Having stomata which open at night, *sedum* species are able to take in CO_2during nighttime, closing in the morning to avoid water loss from transpiration (*Li, W.c., and K.k.a. Yeung, 2014*). Research carried out on *sedum* species have estimated that uptake for an extensive green roof of 100 m² can be around 46% of the annual CO_2 emissions from a standard car driving around 10 km/day under a year (*Collazo-Ortega, Margarita, Rosas Ulises, Reyes-Santiago Jerónimo, 2017*). Finally, extensive green roofs are the least expensive option to install *(Li, W.C., and K.K.A Yeung, 2014).*

1.2.8.) Green roof, CO_2 and 2020

With CO_2 making up the largest percentage of air pollutants released at airports, Swedavia's focus on bringing their personal CO_2 emissions down to neutral is an important goal. However, other large source of CO_2 caused or related to aircraft activities should also be addressed. As aircraft travelling is predicted to increase in the future, it can reasonably be assumed even Malmö Airport will see a rise of travellers in the years to come. As such, it is important to reduce all of CO_2 emissions emitted by or related to Malmö Airport.

With Swedavia having set their neutral CO_2 by 2020 goal, a continuous and updated set of data is thus available, making it easy to obtain CO_2 emissions for all of Malmö Airport, not just Swedavia's own activities.

2) Method

2.1.) Limitations of this study

Limited time and budget restrictions have meant data for average carbon sequestration per m^2 extensive green roof could not be based results from experiments. A previous experiment carried out by Rowe, (*Rowe, 2010)* provides an average carbon sequestration capacity per m^2 of extensive green roofs. Further limitations arise regarding accuracy of carbon sequestration from Rowe's findings. For simplicity in this project, sequestration is assumed to be linear.

Other experiences of similar nature yield much variation in collected results. One paper from Virginia University, *(George, 2012)* seems to render somewhat similar results to Rowe's experiment (*Rowe, 2010*). However, even this paper relies on assimilation rates of carbon from previous scientific experiments (*George, 2012).* A more thorough research from 2014 (*Whittinghill, J. Leigh et.al. 2014)* shows larger carbon sequestration potentials for extensive green roof. Possibly due to newer methods, such as greater variations in *sedum* species or deeper soil substrates, it demonstrates largely diverging results to the other research papers. It was also carried out in the more secluded environments at Dalhousie University and Studley campuses.

As such, Whittinghill's results will not be used for this paper. Both George and Rowe's results seem to converge to similar results. Rowe's earlier experiment on extensive green roofs in Michigan also has a larger relevance for Malmö Airport and Swedavia. Airports exhibit conditions more relatable to urban environments of large cities. Universities, on the other hand, can carry out experiments in more controlled environments, compared to data gathered in urban dwellings, and Whittinghill's results might not be comparable to the situation found at Malmö Airport.

2.2.) Equations

Several steps had to be undertaken in order to calculate a total area of extensive green roof for complete carbon reduction of all major CO_2 emitting sources. To do so, several equations were developed, and can be seen below. Each equation is further explained under its relevant section in method.

- Equation 1; total amount of CO_2 emissions by major sources related to Malmö Airport activity, based on guide data (*See appendix):*

$$\text{Aircraft } CO_2 \text{ emission} + \text{Vehicles and GPU } CO_2 \text{ emissions} + \text{Commuting staff (Swedavia) } CO_2 \text{ emissions} = \text{Total } CO_2 \text{ emissions (tons)}$$

- Equation 2; allowing to calculate CO_2 emissions released by Malmö Airport over time:

$$X * Z = Y$$

X = Time (years) for CO_2 release
Z = Total of equation 1 (*g/CO₂*)
Y = Total CO_2 release by Malmö Airport over period of time (*g*)

- Equation 3; based on Rowe's experiment it provides the total amount of carbon sequestered per m² over time:

$$X * Y = N$$

X= Carbon (*g*) sequestered after certain amount of time
Y= Total carbon sequestered (*g/m² over time*)
N= Amount of six month segments. (*six month= 1 segment, 1 year= 2 segments,...)*

- Equation 4; result provides total area of green roof needed for full CO_2 sequestration of emissions from Malmö Airport:

$$\frac{X}{Z} = Y$$

X= Carbon sequestered m² (*g*) after a certain amount of time
Z= Total CO_2 from three major CO_2 groups
Y= Area green roof (*m²)* for full carbon sequestration

- Equation 5; gives changes in CO_2 binding capacity of extensive green roof over time:

$$\left((23110 * 10^6) * \mathrm{n}\right) - (122\ 275\ 132 * \mathrm{n}) = \mathrm{Y}$$

n= Time passed (*years*)
Y= Carbon sequestration by extensive green roof (*g*)

2.3.) Carbon sequestration per m²

Equation 1:

$$\text{Aircraft } CO_2 \text{ emission } + \text{ Vehicles and GPU } CO_2 \text{ emissions } + \text{ Commuting staff (Swedavia) } CO_2 \text{ emissions} = \text{ Total } CO_2 \text{ emissions (tons)}$$

The most recent emissions of CO_2 by Malmö Airport are found in data gathered by Swedavia in 2016, under the guide section (Appendix, *table 2*). Information was provided by Maria Jonassons, Environmental advisor for Malmö/Ronneby. The three most important CO_2 emitting groups were singled out, as they are responsible for the largest amounts of CO_2 release. Using *equation 1*, total of their emissions (tons), was calculated (*Table 3*). Important to notice is this data does not take into account unexpected CO_2 emissions. Unexpected events represent unforeseen event, such as extreme weather conditions or a larger number of flights, which might increase amounts of CO_2 emissions in unanticipated ways.

2.4.) Malmö Airport and CO_2 release

Equation 2:

$$X * Z = Y$$

X = Time (years) for CO_2 release
Z = Total of equation 1 (*g/CO₂*)
Y = Total CO_2 release by Malmö Airport over period of time (*g*)

The amount of CO_2absorbed by 1m² of green roof is based on an already existing experiment by D. Bradley Rowe, (*Rowe, 2010*). A 2 year monitoring of sedum roofs in Michigan gave an average of total carbon sequestration/m² for extensive green roofs, taking into consideration carbon sequestered both above (vegetation) and below (soil) ground. Rowe also mentions the original carbon content from 1m² of extensive green roof, which must be disregarded in order obtain the true amount of carbon sequestration from ambient air. By using Rowe's data and *equation 1*, calculations on an expected average amount of carbon sequestered after 6 months was calculated. This average was inserted as x in *equation 2*. Multiplication with relevant amount of six month segments (1 year=2 segments, 1.5 years= 3 segments...) provided an extent on amounts of carbon expected to be sequestered per m² of extensive green roof, over a certain period of time.

2.5.) Area Green roof needed

Equation 3

$$X * Y = N$$

X= Carbon (*g*) sequestered after certain amount of time
Y= Total carbon sequestered (*g/m² over time*)
N= Amount of six month segments (s*ix month= 1 segment, 1 year= 2 segments,...)*

Previously released CO_2 adds on to any future emissions. To find out area of extensive green roof needed to bring emissions of CO_2 down to 0, *equation 3* is used, taking into account any added amount of carbon dioxide released over time. Multiplication of total amount CO_2 released (*table 3)* with time allocated for emission release, provides a total of CO_2 over time.

2.6.) Total area of roof at Malmö Airport

Equation 4:

$$\frac{X}{Z} = Y$$

X= Carbon sequestered m² (*g*) after a certain amount of time
Z= Total CO_2 from three major CO_2 groups
Y= Area green roof (*m²)* for full carbon sequestration

Using *equation 4*, the area of extensive green roof required by Malmö Airport for full carbon sequestration is found. Division of total amount carbon sequestered per m² with total CO_2 emission from Malmö Airport (*table 3*) over the same time period, gives area of extensive green roof needed for total carbon sequestration (m²).

To calculate Malmö Airport's total roof area, Geographical Information System (GIS) was used. All dark gray spots in *fig.3 (see results, 3.4)* represent a building area on Malmö Airport premises. Roofed area is assumed to be equal to building area, and an addition of all areas in an excel table *(appendix, table 6)* gave a total roof area for all buildings found at Malmö Airport.

2.7.) CO_2not absorbed by green roof

Equation 5:

$$\left((23110 * 10^6) * \mathrm{n}\right) - (122\ 275\ 132 * \mathrm{n}) = \mathrm{Y}$$

n= Time passed (*years*)
Y= Carbon sequestration by extensive green roof (*g*)

Equation 5 provides information about carbon levels which might remain unbound after 2020. It also provides the increase of unbound CO_2 over time, after potential installation of the extensive green roof. Subtraction of total CO_2 emissions (*Table 3*) and carbon sequestration by the roof over time provides information about amounts of carbon remaining unbound (*table 5, appendix)*.

3. Results

3.1.) CO_2 release by Malmö Airport

Table 3, CO_2 emissions from all 3 major branches related to Malmö Airport, both in tons and as a total percentage.

Emission responsible	**CO_2 release by Malmö Airport (tons)**	**% of CO_2 release**
Aircrafts	**22 607**	**97.83**
Landing Take Off (LTO)	21 823	94.43
Engine Testing	272	1.18
APU	512	2.22
Vehicles and GPU	**263**	**1.14**
Petrol	38	0.16
Diesel incl.GPU 100%	0	0.00
Diesel incl.GPU (Evolution 10% winter)	98	0.42
Diesel incl.GPU (Evolution 32% summer)	127	0.55
Commuting staff (Swedavia)	**240**	**1.04**
car (non-environmental)	207	0.90
Car (environmental)	33	0.14
Bus	0	0.00
Total	**23110**	

Results of *table 3* were calculated using *equation 1*. All major sectors responsible for CO_2 emissions are broken down into more specific subcategories, for a more detailed understanding on amounts CO_2 each sector contributes with annually.

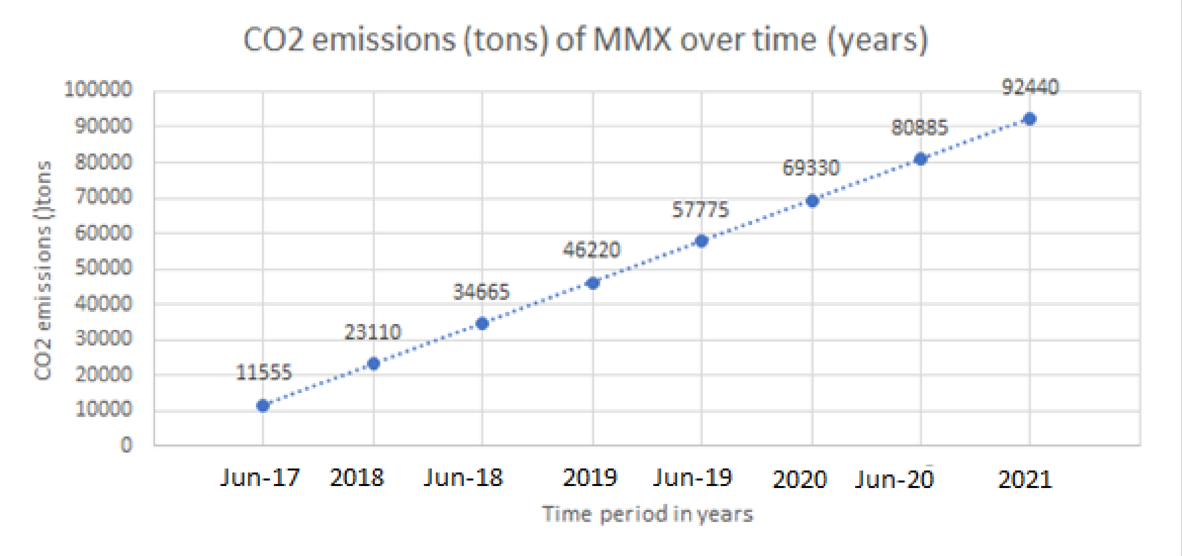
Percentages of total emissions were also calculated, to provide better perspectives on CO_2 emissions each sector represents on the overall scale of annual emission release.

$$22607 + 263 + 240 = 23110 \text{ tons } CO_2$$

Table 3 only provides data for one year of emission release, in 2016. With 3 years remaining before the end of 2020, total amount of CO_2 emissions is found using *equation 3*.

$$23110 * 3 = 69\,330 \; tons\; CO_2$$

Table 3 in appendix shows CO_2 emissions increase from 2017 to 2021. Illustrated in *graph 1*, it is found through use of *equation 2*.



Graph 1, simplified linear increase of CO_2 emissions at Malmö Airport to 2021, starting around June 2017. These results are assumed to be released if nothing else is done to decrease CO_2 emissions at Malmö Airport.

3.2.) CO_2 sequestration of extensive green roof

Average CO_2 sequestration capacity of extensive green roofs was calculated using D. Bradley Rowe experiment. Rowe's experiment showed that 1 188 *g/m²* of carbon were found in 1*m²* of extensive green roof. However, from this number, 810g of all carbon measured was proven to be original substrate. After removal of this original mass, carbon sequestration was calculated to instead be at an average of 378 *g C per m².*

$$1\ 188 - 810 = 378\ gC\ per\ m^2$$

Having obtained the amount of carbon sequestered from ambient air, it was inserted in *equation 3.* In turn this provided the amount of carbon sequestered after half a year.

$$X * Y = N$$

$$X = \frac{Y}{N}$$

$$X = \frac{378}{4}$$

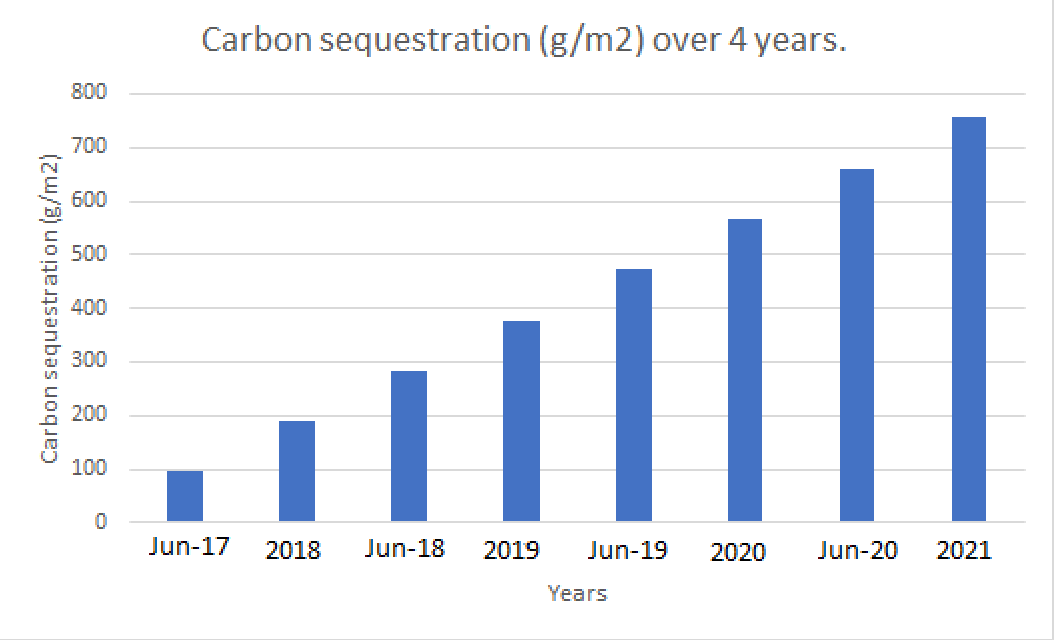
$$X = 94.5\ gC\ per\ m^2 \text{ after half a year}$$

Equation 3 can be used for future calculations of carbon sequestration/m² over time, by changing inserted values (*table 4, appendix*). As such, calculating amounts of carbon expected to be sequestered around 3 years in the future, yields following results:

$\frac{3}{0,5} = 6\ segmetns\ of\ half\ a\ year$

$$X * N = Y$$

$$94.5 * 6 = 567\ gC\ per\ m^2$$



Graph 2 simplified linear carbon sequestrations per m² of extensive green roof, from June 2017 to beginning of 2021.

3.3.) Area of Green roof and carbon sequestration by 2020

Required area of extensive green roof needed for full completion for neutral CO_2 emission by the end of 2020 goal is found through *equation 4*. A conversion of tons to grams must first be done.

$$\left((23\,110 * 10^6) * 3\right) = 69\,330 * 10^6 g\; CO^2 \text{ released after 3 years}$$

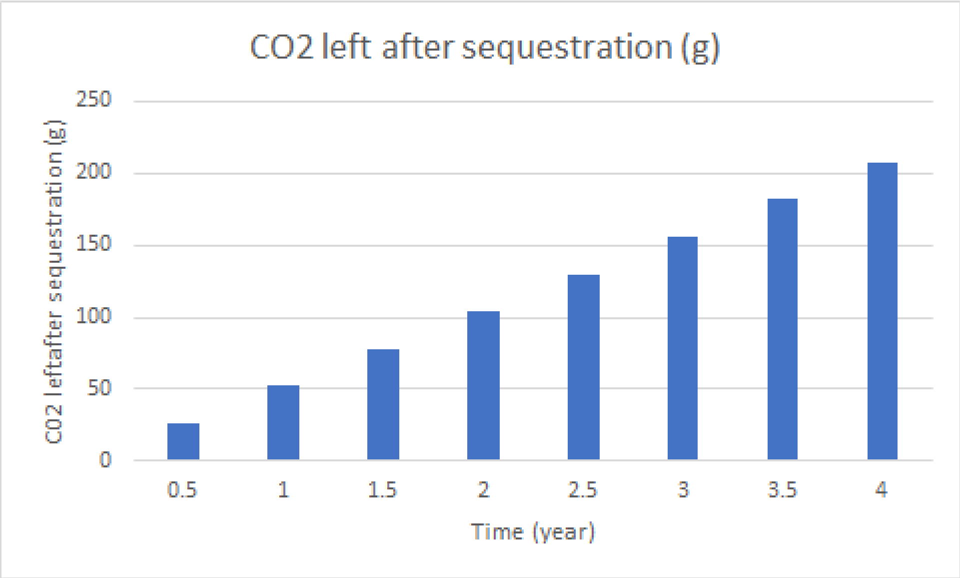
this is then inserted into *equation 4*.

$$\frac{X}{Z} = Y$$

$$\frac{69\,330 * 10^6}{567} = 122\,275\,132 \text{ m}^2\; of\; green\, roof\; needed$$

Ability of extensive green roofs regarding carbon sequestration changes over time, affecting its sequestration capacity. This modification in sequestration ability is reflected in *table 5, appendix*, and calculated using *equation 5*. Area of extensive green roof needs to be multiplied with carbon sequestration ability of time period looked for (*table 4*). This result is then subtracted to the CO_2 emitted under that same time period, to yield results seen in *graph 3*.

$$\left((23\,110 * 10^6) * n\right) - \;(122\,275\,132 * n) = Y$$
$$\left((23\,110 * 10^6) * 0.5\right) - \;(122\,275\,132 * 94.5 = 26\; g$$



graph 3. Amount CO_2 left after carbon sequestration of extensive green roof over time.

3.4.) Malmö Aiport total roof area

Geographical Information System (GIS) made it possible to find a map of Malmö Aiport's area. This map included any building found on Malmö Airport premises, with dark grey shapes in *fig 3* representing building areas. By hovering with the mouse on top of each building in the program, area for that particular building was given. Addition of these building areas in an excel sheet provided a total roofed area for Malmö Airport. This can be seen in *Table 6 (appendix),* and is calculated to be 77 318.5 m².

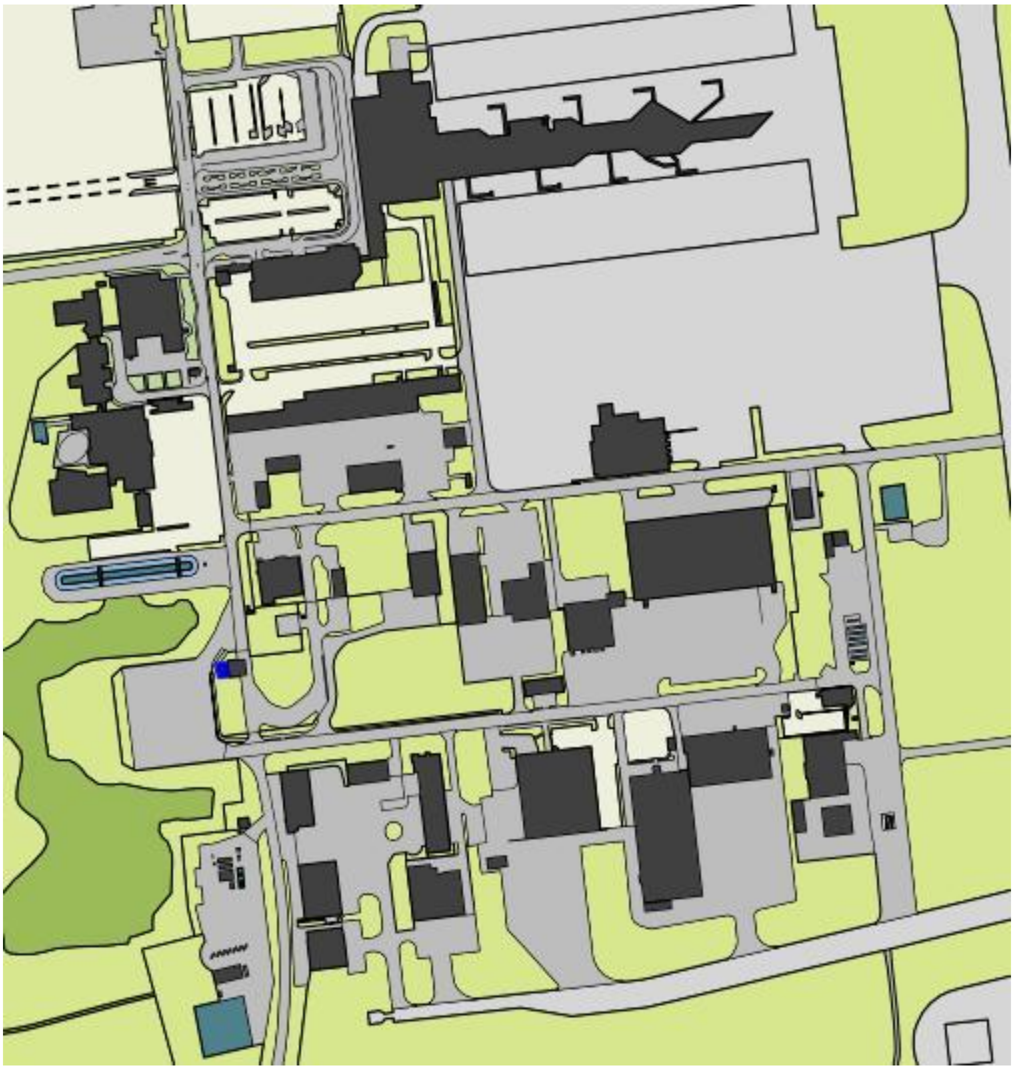


Fig. 3, Map of Malmö Airport. Dark grey areas are buildings. Lighter grey shapes represent paved ground, with no buildings, green shapes are fields and forest patches.

4) Discussion

The aim of this research was to figure out if an installation of extensive green roof at Malmö Airport could reduce CO_2 emission of all major sources to neutrality by 2020. Even though vegetation on green roofs have the ability to bind air pollutants and sequester carbon, final results of this paper shows that Malmö Airport does not have enough roof are available. Calculated area required for such a task would be equivalent to 1 580 additional airport roofs the size of Malmö Airport.

Overall carbon sequestration per m² of extensive green roof and total CO_2 emissions of Malmö Airport allowed the plotting a trend for carbon sequestration over time (*graph 2)*. In turn, these results allowed estimations regarding area size of green roof required for achievement of a neutral CO_2 airport by the end of 2020. Currently, not much research exists on green roofs and their ability to bind carbon. As such, findings in this paper could represent a valuable source of information for future research regarding extensive green roofs and carbon sequestration.

4.1.) CO_2 release by Malmö Airport

In *Table 3*, it is shown that aircraft related emissions of CO_2 make up the majority of all emission at Malmö Airport. More specifically, LTO activities stand for 94.43% of CO_2 release. When comparing this large percentile to commuting Swedavia staff at 1.4% and GPU/vehicles at 1.14% CO_2 emissions, the latter two sectors are next to negligible. However, once put into actual amounts of emission release, staff and GPU/vehicles release a combined 503 tons CO_2 a year. Not as large as the 22 607 tons created by the aircraft sector, it still represent a rather considerable mass of CO_2 production.

Amount of CO_2 expected to be emitted each year by Malmö Airport might vary from year to year, increasing or decreasing depending on various factors (weather, improved and more efficient engines, green fuel...). If assumed to be linear, the flux of CO_2 emissions needing disposal increase over time, one year of CO_2 emission yields 23 110 tons CO_2, two years of emissions yield 46 220 tons and four years 92 440 tons. To achieve a neutral CO_2 emission by 2020, there needs to be a complete disposal of total increase CO_2 over time. As such, annual growth factors must be taken into account before any potential installation of extensive green roofs can be considered. By the end of 2020, Malmö Airport is expected to release a total of 69 330 tons CO_2, mainly from LTO activities in the aircraft sector.

4.2.) CO_2sequestration of extensive green roof

In his experiment, Rowe noted that large amounts of this bound carbon were found to be pre-existing within plants and soil on the roofs. Of 1 188 g C per m^2, only 32 % of the carbon was sequestered. This means that around 68% of carbon found in substrates was originally present. Rowe therefore concludes that only a very low amount of carbon is actually sequestered from surrounding air, with a majority already found in substrates from roof.

Half a year of carbon sequestration is expected to be around 94.5 g C m^2. These results are relatively close to George's finding of 75 g C m^2 for half a year (*George, 2012*). In contrast, Whittinghill found an ability to sequester 4 197.7 g C m^2 after half a year (*Whittinghill, Leigh J, 2014*). As limited time for this paper did not allow any first-hand data collection, Rowe's results are of extreme relevance to this paper.

A fivefold increase is seen in carbon sequestration capacity after 2.5 years. During this time, carbon binding capacity of extensive green roofs goes from 94.5 g C m^2 to 567 g c m^2. With 3 years remaining before the end of 2020, this noted increase in binding capacity represents a positive and relevant factor. Furthermore, carbon binding abilities of extensive green roofs do not stop after 3 years. As seen in *graph 3*, they further increase, and from 2020 to 2021, they go from 567 g C m^2 to 756 g C m^2. However, this increase might cease after some time and further research should be done regarding this possibility.

Other research, has estimated that 100 m^2 of *sedum* extensive green roofs can bind around 46% of annual CO_2 emissions from a standard car, driving around 10 km per day *(Collazo-Ortega, Margarita, Rosas Ulises, Reyes-Santiago Jerónimo , 2017)*. Representing an intake of less than half of all CO_2 emissions from a standard car, with a set limit of 10 km in distance travelled, these are not ideal results. Compared to the aircraft sector releasing much more CO_2 and covering more ground at higher speeds than these standard cars, it is not enough. In fact, it would means very little carbon of the overall CO_2 emissions released Malmö Airport are likely to ever be sequestered. Nonetheless this research gives an interesting insight in efficiency of extensive green roof regarding carbon sequestration.

If able to mix more vegetation on these green roofs, carbon sequestration capacity might increase. Studies have shown that trees are able to reduce air pollution in urban areas (*Chen, Chi-Feng, 2015)* and can also sequester more carbon on a global level than any other vegetation (*Collazo-Ortega, Margarita, et.al, 2014).* They have been found to provide the highest air pollution removal capacity of all green infrastructures (*Jayasooriya, Varuni, et.al., 2016*). Extensive green roofs on the other hand are low in biomass and have little potential to offset carbon emissions in cities.

However, recent research carried out in 2014, with larger variation of vegetation species and soil depth have proven to sequester over 4 000 g C per m² (*Whittinghill, Leigh J, 2014*). This could mean that extensive green roofs could make more significant contributions as urban carbon sinks than originally thought.

4.3.) Area of roofs

Malmö Airport's roof area was determined using GIS, it provided areas of buildings, not specifically of roofs. This might mean that actual roof areas of Malmö Airport could be smaller or larger than calculated. However, it is nowhere near close the 122 275 132 m² of extensive green roof needed, to being able to host that large of an extensive green roof area. In fact, the area required equals an additional 1580 Malmö Airport airports.

One benefit obtained from its installation, however, would be its continuous and ever so slightly increasing capacity to bind carbon over the long run. By the end of 2021, an area of 122 275 132 m² extensive green roof would bind nearly 92 439 tons carbon, one ton less than the 92 440 tons expected to be emitted by Malmö Airport in 2021. Then again, the equilibrium factor where plant growth= plant decomposition will eventually take place, reducing efficiency of the extensive green roof. As plants release CO_2 through respiration and decomposition of their organic material (carbon) (*Gougoulias, Christos, 2014*), it can result in more CO_2 being produced. When *Sedum* plants release CO_2 during daytime, they do not fully compensate this with a nighttime uptake *(Agra, Har'el, et al, 2017*), making them not ideal for carbon binding.

4.4.) Unbound CO_2

After installation of an extensive green roof, there would still be a small amount of CO_2 remaining unbound. As mentioned previously, carbon binding ability of substrate matter increases over time, the same being true for CO_2 emissions at Malmö Airport. A much larger increase of CO_2 release from the airport might cancel out potential benefits of an increasing carbon binding capacity by the roof. From 2018-2020, a period of two years, CO_2 emissions increase 46 220 tons. Within the same time lap, carbon binding capacity of extensive green roofs only increases with 378 g per m².

4.5.) Challenges and improvement

For future research, original data would provide more certainty to the research. Using more updated research as well as comparing data from other experiments would further strengthen the precision of calculations. On a more global note, little research exists regarding extensive green roofs and their ability to sequester carbon.

As such this paper represents a relevant source of information for future projects interested in investigating this matter. As extensive green roofs tend to be limited to *sedum* species, they are not the most efficient when it comes to carbon binding. As such, intensive green roofs should be researched on, as they can hold a larger variety of vegetation, potentially proving more efficient in carbon, especially if possibilities of including trees on rooftops exist.

5) Conclusion.

- Extensive green roofs carbon sequestration capacity increases over time, but it is not known how long this increase continues.
- This increase is much too small compared to CO_2 amounts released by Malmö Airport.
- Using extensive green roofs at Malmö Airport to reach CO_2 neutrality by 2020 is not possible.

Unclean air affects both populations and the environment. Carbon dioxide, the main greenhouse gas is of major concern, as it represents a large majority of emissions released today. In the aviation sector alone, CO_2 makes up around 72% of emissions. As aviation experiences a steady and annual growth due to increased popularity of air travelling, CO_2 emissions are an issue needing to be addressed.

Using Malmö Airport as an example, possibilities of achieving neutral CO_2 emission for major sectors related to the airport by an installation of extensive green roofs alone proved impossible.

Previous research shows a low amount of carbon sequestration by *sedum* plants. Although this capacity increases over time, the gap between carbon sequestration and CO_2 emissions of Malmö Airport turned out to be too large. An area of 122 275 132 m² extensive green roof would need to be installed for CO_2 emissions to be reduced to neutrality by the end of 2020. As roofed areas of Malmö Airport currently amounts to 77 318.5 m², it is nowhere near a fraction of the area required. Furthermore, an installation of such a roof would require time and emit CO_2, resulting in opposite effects. However, Swedavia has undertaken several other steps for a total reduction of their own CO_2 emissions. Several of these include better engine performance and green fuel. Currently not applied to aircraft emissions, they are nonetheless of great relevance, as it might be used to reduce overall emissions of all airport related activities in the future.

Still, green infrastructure should not be disregarded for future uses. Many other airports having installed green roofs experience benefits in term of increased biodiversity, insulation, stormwater management and trapping of other air pollutant (PM, VOC, Nox). As such, an installation of extensive green roofs at Malmö Airport could still prove beneficial and should not be disregarded in Swedavia’s future work for sustainable airports.

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Appendix

Table 2, Data report from Swedavia, regarding amount of CO_2 released by Malmö Airport in 2016.

Guide (Scope3)	23435		47 %
Aircraft		**22607**	
LTO	21823		
Engine testing	272		
APU	512		
Energy		**0**	
Electricity (Marked Based Method)*	0		
Vehicles and GPU		**264**	
Petrol	38		
Diesel incl GPU 100%	0		
Diesel incl GPU (Evolution 10% Winter)	98		
Diesel incl GPU (Evolution 32% Summer)	127		
Commuting staff (Swedavia)		**240**	
Car (Non environmental)	207		
Car (Environmental)	33		
Bus***	0		
Airport waste		**324**	

Table 3 shows the expected increase in CO_2 (tons) at Malmö Airport emissions after a certain amount of time, portrayed in years, from 2017 to 2021.

time (years)	CO_2 emissions (tons)
0.5	11555
1	23110
1.5	34665
2	46220
2.5	57775
3	69330
3.5	80885
4	92440

Table 4 shows carbon sequestration in g/m² of extensive green roofs, over a period of time. For simplicity and better understanding, time is shown in years and not six month segments.

Carbon sequestration (g/m²)	**Time period (years)**
94.5	0.5
189.0	1.0
283.5	1.5
378.0	2.0
472.5	2.5
567.0	3.0
661.5	3.5
756.0	4.0

Table 5 , Amount of CO_2 (g) not sequestered by area of extensive green roof that would have to be installed at Malmö Airport for a CO_2 emission rate of 0 by 2020.

CO_2 left after carbon sequestration (g)	**time (year)**
26	0.5
52	1.0
78	1.5
104	2.0
130	2.5
156	3.0
182	3.5
208	4.0

Table 6, the roofed area (m²) of Malmö Airport added up as a total.

Name of building	area (m²)
Terminal	14828.96
Operation building	4013.23
Tower	190.4
Water plant	44.29
Firestation	2881.85
Security central	240.9
Inspection	368.24
Field pavilion	1423.93
Shipping building	1391.44
Catering	1037
Field parking	2947.19
Shipping terminal	1725.15
Parking house	3020.17
Offices	391.8
Main Gate	209.52
Environmental station	36.14
Heat central	53.66
Goods terminal	395.02
Shipping terminal	7417.19
Field parking	594.31
Mechanic building	266.96
Sun building	18.95
Sand building west	61.61
Sand building east	61.98
Field station	372
919	3020.17
372	129.9
924	2906.35
174	955.89
1038	1282.01
844	3060.19
125	1524.95
925	324.01
717	303.24

1008	1157.07	464	48.62
290	249.88	382	116.52
849	828.01	516	26.25
110	1763.99	454	58.77
56	5196.64	**Total area**	**77318.58**
436	69.87		
941	4353.58		
938	1608.24		
933	1759.8		
934	951.26		
935	1343.48		
273	288		