

**BUILDING-INTEGRATED BIOTIC CARBON SEQUESTRATION
TECHNIQUES: OVERVIEW AND SIMULATION WORKFLOW**

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BUILDING-INTEGRATED BIOTIC CARBON SEQUESTRATION TECHNIQUES: OVERVIEW AND SIMULATION WORKFLOW

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LIST OF SYMBOLS AND ABBREVIATIONS

CS	Carbon Sequestration
VGS	Vertical Greenery System
GHG	Greenhouse Gas
CO ₂	Carbon dioxide
CAM	Crassulacean Acid Metabolism
TE	Total Energy
IPCC	Intergovernmental Panel on Climate Change
PAR	Photosynthetically Active Radiation

SUMMARY

There is enough scientific consensus that anthropogenic climate change is a reality of our times. According to a report from the National Academy of Sciences (National Academies of Sciences, Engineering 2019), “By mid-century, the world needs to be removing about 10 billion metric tons of carbon dioxide out of the air each year. That’s equivalent of about twice the yearly emissions of the U.S.” To achieve this goal, the act to cease the emission of greenhouse gases (GHGs) alone is not enough. It is important that the structures which cover a large area of the earth start contributing to Carbon Sequestration (the process of capturing carbon from the atmosphere and storing it securely) at a massive scale. To accomplish that, a thorough understanding about building-integrated Carbon Sequestration techniques, including their mechanism, prerequisites as well as consequences, is essential.

This study aims to 1) Provide an overview of building-integrated Carbon Sequestration (CS) techniques focusing on their potential environmental impact and associated costs. CS techniques are classified into three categories: a) Biotic techniques (vertical greenery systems (VGS), Green Roofs and algae facades); b) Materials (carbon-negative and carbon absorbing building materials); and c) Equipment (filter towers). 2) Conduct a comparative analysis specifically showing both the CS potential and design factors associated with the Biotic CS techniques to allow architects and designers to evaluate these technologies and analyze their integration potential in architectural practice based on both the factors. 3) Propose a modeling framework to estimate the amount of carbon that can be sequestered by a structure that utilizes biotic elements to enhance environmental performance. The proposed workflow accounts for site and climate-based variations in solar radiation across

the globe, as well as different plant types, species, the type of photobioreactors in the case of micro-algae, and their energy conversion efficiency ratios.

Preliminary literature review shows that Green Roofs and vertical gardens can capture $150\text{gC/m}^2 - 650\text{gC/m}^2$, while algae facades go up to $2430\text{gC/m}^2 - 2970\text{gC/m}^2$. Biomass and filter towers could absorb a relatively high amount of approximately $1 \times 10^{15} \text{ g C}$ and $687.5 \times 10^9 \text{ g C}$, respectively (without normalization). By analyzing and summarizing each CS technique based on performance indicators like prerequisites, initial and maintenance costs and area required, various schematic design considerations and research gaps are laid out. Further, the proposed modeling framework showcases the CS potential of the three biotic techniques in the context of five major Koppen classified climate zones – tropical, dry, moderate, continental, and polar. The workflow for algae facades is validated against measured data from collected information in practice from the BIQ house in Germany and Photo.synth.etica by EcologicStudio. A workflow is formulated specifically for Green Roofs and VGS from previously published literature by (Getter et al. 2009), (Whittinghill et al. 2014), (Pulselli et al. 2014), and (Kuronuma et al. 2018). This thesis presents a framework to employ CS integration in the built environment, and discusses advances needed in order for buildings to not just limit the catastrophic effects of climate change, but also mitigate it for a better future for our built environment.

CHAPTER 1. INTRODUCTION

1.1 Background

Anthropogenic climate change is a reality of our times (Cawley 2011). The greenhouse effect which has made life on Earth possible by absorbing the sun's radiation and keeping the Earth's surface warm is now becoming one of the causes of climate change. A number of greenhouse gases (GHG) such as methane (CH₄), carbon dioxide (CO₂), water vapor, ozone (O₃) contribute to this process (Farrelly et al. 2013), out of which CO₂ is the most dominating absorber after water vapor and clouds. (Schmidt et al. 2010). Due to anthropogenic activities, the amount of CO₂ has seen a drastic rise from 270 $\mu\text{mol}\cdot\text{mol}^{-1}$ to concentrations higher than 385 $\mu\text{mol}\cdot\text{mol}^{-1}$ in the last two centuries estimated to result in a temperature rise of 3-5⁰ C by the year 2100 (IPCC 2014). Such an increase in emissions of carbon might push our planet to cross a threshold beyond which Earth's stabilization could not be achieved by human actions (Oreskes 2004). Thus, the fate of this planet may lie predominantly on mastering the ability to cycle carbon efficiently and avert it from becoming the reason for the destruction of humankind (Antonietti and Müllen 2010).

1.1.1 Carbon Sequestration

Carbon Sequestration (CS) is the process of capturing carbon from the atmosphere and storing it securely (Jain et al. 2012). This is largely undertaken to reduce the excessive carbon dioxide (CO₂) concentration in the air caused by industries, burning of fossil fuels, automobiles, which otherwise lead to heat being trapped, resulting in global warming (Sood and Vyas 2017).

According to a report from the National Academy of Sciences (National Academies of Sciences, Engineering 2019), “10 billion metric tons of CO₂ needs to be removed out of the air each year. That’s equivalent of about twice the yearly emissions of the U.S.” In order to achieve this goal, the act to cease the emission of GHGs alone is not enough (Nasa 2016).

Moreover, while forests, soils, and oceans have been major, as well as the oldest, carbon sinks, there have been several pieces of evidence of their deterioration such as water acidification and changes in the soil content, due to increased anthropogenic carbon emissions (Sundquist et al. 2008). As per IPCC’s report, it is required to halt the temperature rise 1.5⁰ C above pre-industrial levels otherwise it would lead to worse heatwaves, drought and flooding. (Zhou 2018). To avert this, it is important that the structures which cover large areas of the earth start contributing to Carbon Sequestration (CS). The integration of CS techniques in architecture has increased significantly recently even though some of the techniques mentioned in this literature review, like vertical gardens and Green Roofs, were being used in buildings for a long time, however, for other purposes.

1.2 Research Overview

1.2.1 Aim and Objectives

The aim of this thesis is to create a taxonomy of CS techniques that can be integrated with the built environment and consolidate the influencing design factors to enable the prediction of biotic techniques’ CS potential at the schematic design stage.

The objectives of this research are:

- To recognize Carbon Sequestration techniques in the built environment that are useful from a Climate Change mitigation perspective.
- To evaluate Carbon Sequestration technologies and analyze their integration potential in architectural practice based on CS potential, scale, usability, and maintenance.
- To identify literature and research gaps when focusing on scholarship relevant to Carbon Sequestration integration in the built environment.
- To propose a modeling framework to estimate the amount of carbon that can be sequestered by a structure that utilizes biotic methods to enhance environmental performance.

1.2.2 Target Audience

Although a significant number of architects are directing their projects towards addressing issues of Climate Change, they are mainly concentrating on the adaptation aspects of it. Therefore, this thesis, which thoroughly covers various building-integrated Carbon Sequestration techniques, will allow them to consider the aspect of reverting anthropogenic Climate Change. The developed tool's workflow will enable architects to quantify the amount of carbon sequestered by the built environment at an early design stage. In addition, consideration of the CS techniques will equip designers with cutting-edge technologies that should have a positive environmental impact through design. Researchers, architects and students aiming to learn from the state-of-the-art in mitigating the effects of Climate Change will be exposed to a comprehensive review that will enable their scholarship and

research-based practice to not just reduce their impact, but also transform it to be net positive.

1.2.3 Methodology

What are various CS techniques that have been integrated in buildings? As an architect or a designer, what design factors can be considered to incorporate a CS technique to a building typology? How much carbon can a structure capture? To address these questions, this study employed an exploratory research method. Various precedent studies published in peer-reviewed journal and conference papers on building-integrated CS techniques, which were retrieved by a database search were reviewed for a systematic literature review. This being a comparatively recent topic, information was also collected from articles and reviews of reliable governmental and organizational websites. Subsequently, CS techniques were classified into various categories based on similarities in their working mechanism or prerequisites for implementation. Further in the study, comparative analysis was used as a tool to evaluate various CS techniques.

After getting an overview of the CS techniques, the factors affecting the CS potential of biotic techniques were specifically studied in detail. The parameters were divided into constants and variables. To design a universal workflow which could be used to calculate the carbon sequestered by a structure in any part of the world, various aspects such as solar radiation in a location, orientation and area of the building elements were made the primary drivers of the simulation workflow. Finally, the workflow was formulated specifically for biotic techniques using Rhino and grasshopper interface. Various honeybee and ladybug components were used to get the inputs and visualize the outputs in an engaging way. It

was further validated using the results of the case studies found in previously published literature.

The simulation workflow was updated based on the results and percentage errors from the validation process. In the end, it was used to calculate the CS potential range in the Koppen classified climatic zones to understand the varied range of carbon that can be sequestered and the impact of a particular technique in a region. The thesis concluded by discussing the results and a process for strategic planning of CS techniques during the design stage, which may lead to buildings contributing to the efforts of climate change mitigation.

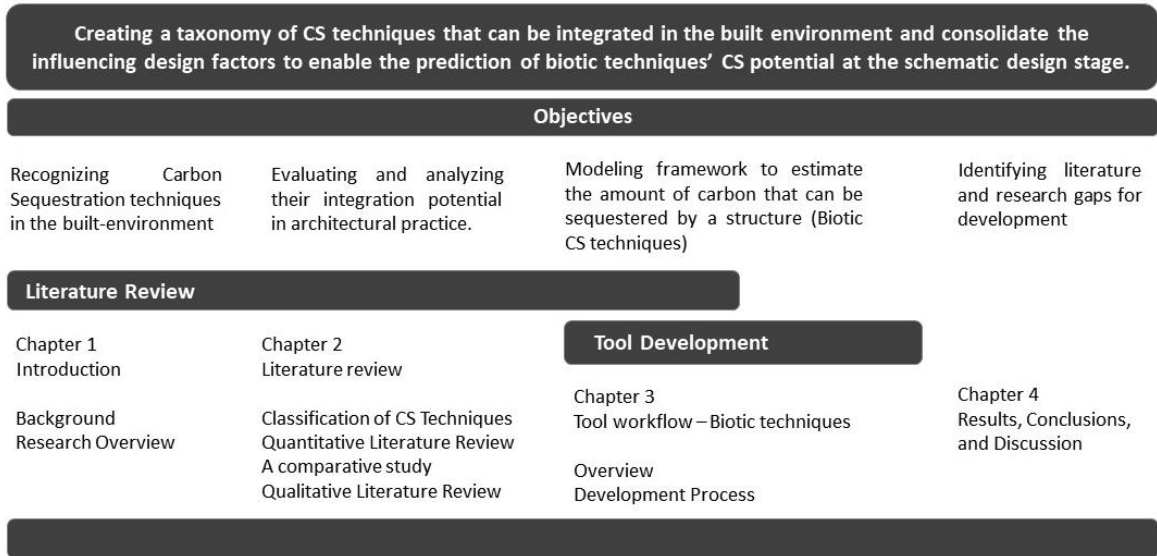
1.2.4 Study Plan

This thesis is presented in four chapters broadly divided into two parts – Literature Review and Tool Workflow. Figure 1 below provides a thesis overview by combining the aim, goals, methods, and chapters.

Chapter 1 introduces the meaning and need for building-integrated CS techniques and provides an overview of the research process. Chapter 2 proposes a classification of CS techniques into three categories – Biotic Techniques, Materials and Equipment, based on a broad literature review. It further provides an extensive quantitative literature study for biotic CS techniques followed up by a comparative analysis and a qualitative literature review for the CS techniques under the category Materials and Equipment. Chapter 3 describes the design factors affecting the CS potential of biotic CS techniques and the development of the framework for calculating the CS potential of these techniques when applied to a structure. It subsequently presents the validation for the workflow using

measured data from previously published literature. Chapter 4 is the final chapter that evaluates and concludes the findings and provides the future scope of research.

Figure 1 - Thesis overview flowchart



1.2.5 Scope and Limitations

This research takes into account CS techniques that have either been applied or demonstrated in the field of architecture. While an attempt to conduct a systematic literature review was made, there are a few limitations in this study. The site used to search published literature was googlescholar.com and thus, literature that has not been published online or does not fall under the search domain of this site might have been left out. The published literature reviewed in this study are from the English language domain and falls only under the year span of 2000 – August 2020 to prevent the inclusion of any obsolete technique in the literature review. Thus, anything published before or after this time or written in any other language is not included. Moreover, few techniques are patented and approved by some labs and universities, however, their scientific literature is not readily

available online. Thus, a cluster of information has been taken from their websites and reports. The scope and limitations of the tool workflow will be discussed later.

CHAPTER 2. LITERATURE REVIEW

2.1 Classification of CS techniques

To classify the CS techniques into different categories, it was important to investigate existing CS techniques that have been integrated with the built environment. With googlescholar.com chosen as the search engine, various combinations of keywords were tried, and the search was limited with the use of advanced search techniques including fixed phrases, AND, OR search, and time frame (Table 1). After the search, since most of the records were published between the years 2000-2020, that date range was chosen as the range of years for this study. Further, two search results were found to be the most relevant based on the records that were seen - **"Carbon Sequestration" OR "carbon capture"** and **"Carbon Sequestration" in buildings OR "carbon capture" AND buildings**. Finally, being closer to the intent and topic of the study, the latter was chosen to take the research forward.

Table 1 - Result of search keywords for the classification of CS techniques

Platform	googlescholar.com	No. of records	2000 - 2020
Keywords	Carbon Sequestration	742,000	464,000
	"Carbon Sequestration"	383,000	231,000
	Carbon Sequestration in buildings	61,500	19,400
	"Carbon Sequestration in buildings"	7	6
	Carbon Sequestration in built environment	82,600	22,700
	"Carbon Sequestration in the built environment"	1	1
	Carbon Sequestration in architecture	59,800	18,800
	"Carbon Sequestration in architecture"	0	0
	Carbon Sequestration techniques	221,000	26,200
	"Carbon Sequestration techniques"	338	319
	building-integrated Carbon Sequestration techniques	11,700	11,400

"building-integrated Carbon Sequestration techniques"	0	0
Carbon Sequestration OR carbon capture	2,950,000	1,810,000
"Carbon Sequestration" OR "carbon capture"	18,500	17,900
Carbon Sequestration in buildings OR carbon capture in buildings	18,200	18,200
Carbon Sequestration in buildings OR "carbon capture in buildings"	7	6
"Carbon Sequestration" in buildings OR "carbon capture" in buildings	32,300	16,800
"Carbon Sequestration" in buildings OR "carbon capture" AND buildings	17,500	17,200

Out of the 17,200 records found for the research, 1000 most cited published papers were identified using the Harzing's Publish or Perish tool (Harzing 2016). These 1000 records along with 51 records from other sources like online web pages of the companies producing CS techniques, found using a general search on google, were screened. Only 169 records were included after the screening of the abstract/title. After a full paper/webpage screening, only 94 records were used for the classification of the CS techniques as shown in Figure 2. These records were limited to their use for classification, and new keyword research was done for each category separately to get more detailed and specific results.

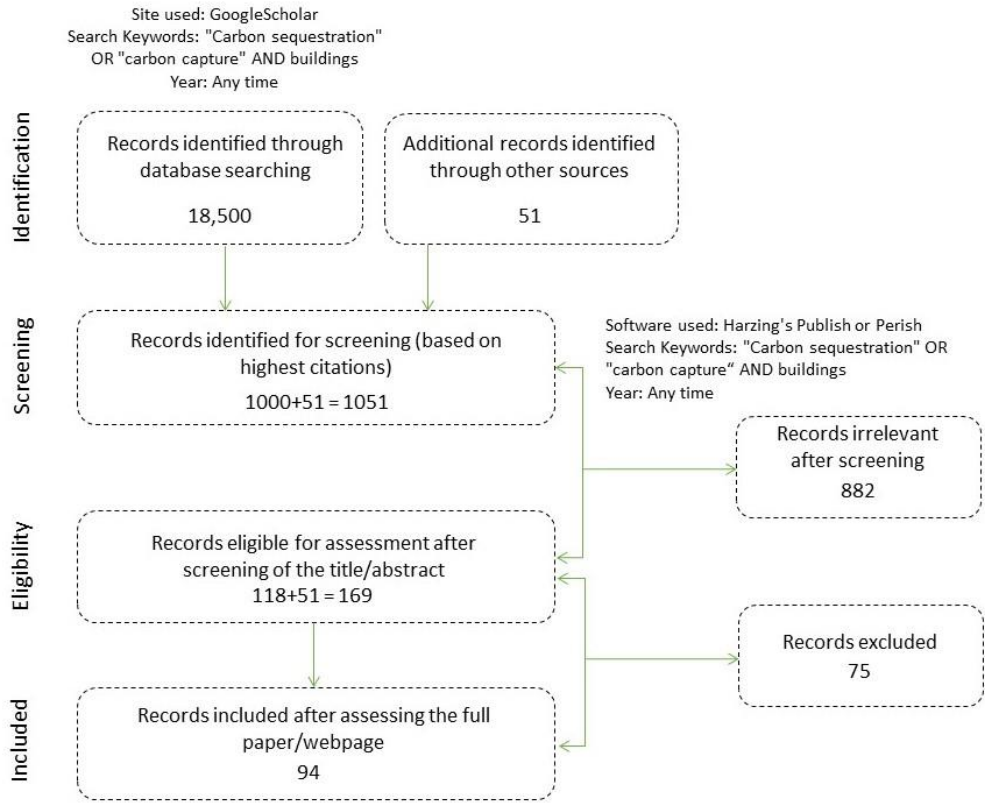


Figure 2 - Literature review process for classification of Carbon Sequestration techniques

Finally, after a systematic literature review, building-integrated CS techniques were proposed to be categorized into three major groupings – Biotic, Materials, and Equipment (Figure 3). Materials and Equipment are in their emerging stages for the purpose of Carbon Sequestration, when compared to Biotic techniques. Therefore, limited information was found when focusing on cost and maintenance. Consequently, they were both not reviewed as extensively as Biotic techniques in the sections to follow.

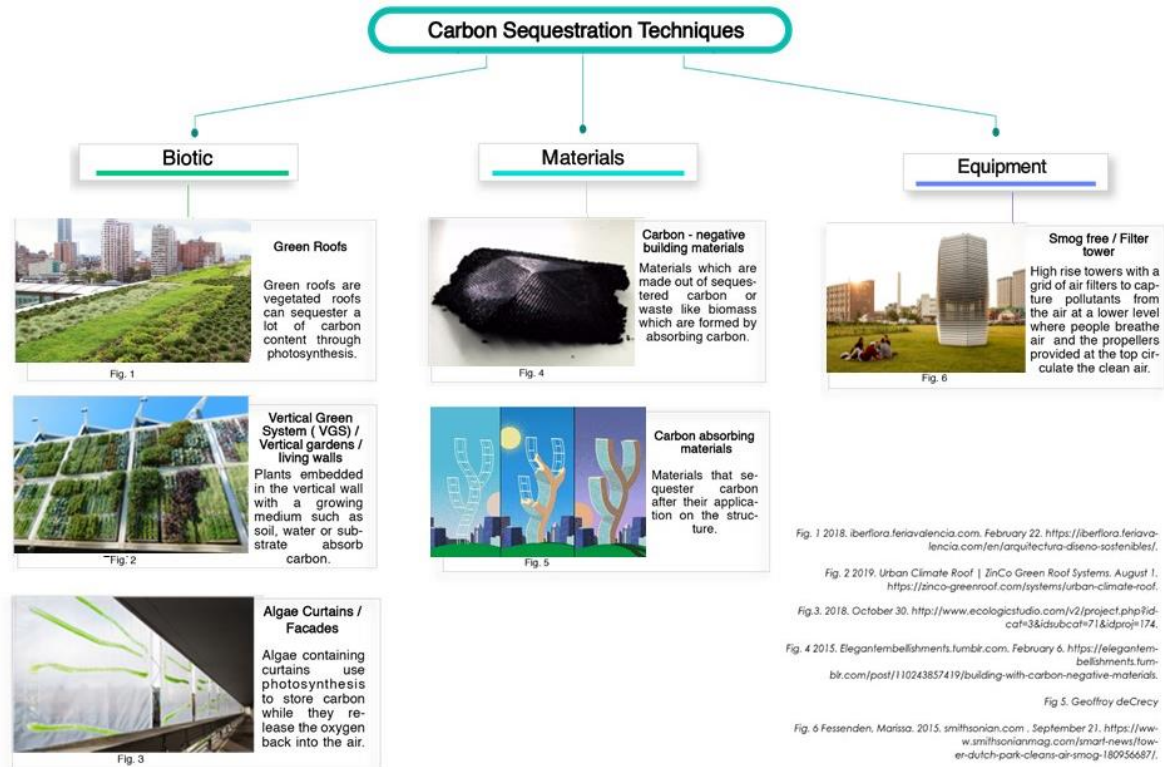


Figure 3 - Proposed classification of Building-integrated CS techniques

2.2 Quantitative Literature Review

2.2.1 Biotic Techniques

Living organisms such as trees and plants, often termed as biotic (Lal 2008) are one of the major sources of CS (Getter et al. 2009). The process of photosynthesis that allows them to assimilate atmospheric CO₂ and release back O₂ falls under the biotic process of carbon sequestration. The carbon absorbed is partially stored in biomass and partially in the roots where it reaches the soil. Surprisingly, the amount of carbon held by the soil is almost double as that by the atmosphere (Kell 2012). Biotic elements are, thus, used in various forms to sequester carbon, out of which Green Roofs and VGS are commonly used techniques (Pérez et al. 2014). To quantify the amount of carbon sequestered by each

technique, a literature study was conducted using specific keywords for each. The records were divided into five categories.

- **Direct:** Papers that include measurement of the CS potential of the techniques and give out values as the first-hand information.
- **Literature Review:** Papers that provide CS potential values accumulated from other resources. They are the secondary sources of information.
- **Indirect:** Papers that mention the Carbon Sequestration potential of the techniques but neither do they measure it themselves, nor do they provide any quantitative analysis.
- **Websites:** Official webpages of the manufacturers of the product.
- **Articles:** Written about the products online.

2.2.1.1 Green Roofs

Green Roofs are vegetated roofs which have been established for around 100 years. They were introduced with the objective of meeting urban environmental challenges and rising cost of land in places such as the United States, Canada, United Kingdom and Germany. They are generally divided into three categories – Intensive, semi-intensive and extensive Green Roofs (Li and Yeung 2014).

- Working Mechanism and Prerequisites

Imitating landscape on a part of a structure may be a challenging process. Specifically, with having to deal with the extremities on the rooftop, it takes 9 layers to fabricate a working Green Roof (Figure 4). The first and the topmost one is the vegetation layer followed by

the growth substrate layer where the growing medium is laid. The type and properties of the substrate chosen has a huge influence on the growth rate of vegetation and the Green Roof's performance. Filter layer as well as drainage layer are provided below that. While the drainage layer controls the intake and outtake of water required by the vegetation and the substrate, the filter layer separates the substrate layer and the drainage layer to prevent clogging of the latter. Other layers include protection layer, root barrier, insulation layer and the water proofing membrane. These layers might not contribute to the working of a Green Roof, but they have a critical role. Any issue with these layers like leakage leads to the failure of the Green Roof. Rectification in these layers also increases the maintenance cost significantly (Vijayaraghavan 2016).

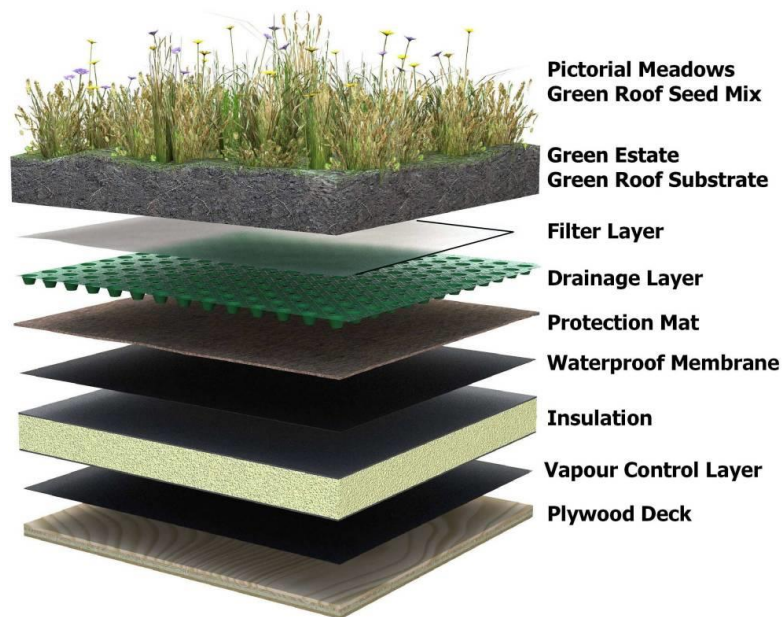


Figure 4 - Structure of a Green Roof

(Credit: (Vijayaraghavan 2016))

- CS Potential

Green Roofs have been used for various purposes such as improving stormwater management, energy saving, mitigating urban heat island effects, but not mainly for CS (Getter et al. 2009). Various keywords with phrases, most apt being, Green Roof Carbon Sequestration and Green Roof CO₂ sequestration, were used to search for records mentioning the CS potential of Green Roofs. Out of total 22 published papers, only 7 directly provided the CS potential values of Green Roofs, excluding 2 literature reviews (Figure 5).

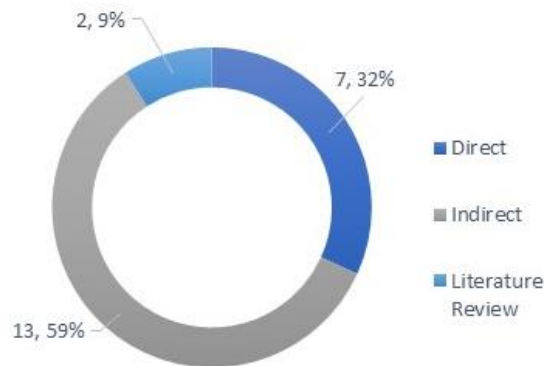


Figure 5 - Records determining the CS potential for Green Roofs

The first study, which was conducted by Getter et al, was performed more than a decade ago in 2009. They conducted 2 studies which included 13 roofs in Michigan and Maryland. All the roofs (1-6 years old) primarily comprised Sedum species and substrate depths ranging from 2.5 to 12.7 cm. After continuous evaluation for 2 years, they found that the above ground plant material sequestered an average of 168gC/m², with the average being 107gC/m² and 913gC/m² for belowground biomass and substrate carbon content, respectively. It was concluded that the entire extensive Green Roofs could sequester

375gC/m² (Getter et al. 2009). The second research was performed by Kuronuma in 2018. They calculated the annual CS potential of Green Roofs by three species to be 459.3g C/m² - 681.9g C/m². The study shows how carbon capture depends on various factors such as the plant species, substrate, the age of the Green Roof, wind speed (Kuronuma et al. 2018). While most of the studies recorded CS values on the lower side of the spectrum, a study by Whittinghill showed enormously high values of 4.67 g C/m² – 65.25 g C/m² (Whittinghill et al. 2014). Although, the values might be correct due to varying factors, the results have been considered an anomaly for this study. Various CS potential values for Green Roof are shown in Table 2.

Table 2 - CS Potential values for Green Roofs

<i>Reference</i>	<i>Annual CS Potential (kg C/m. sq.)</i>
<i>(Getter et al. 2009)</i>	0.375 (Extensive)
<i>(Whittinghill et al. 2014)</i>	4.67 – 65.25 (Anomaly)
<i>(Luo et al. 2015)</i>	6.47 (Intensive)
<i>(Kuronuma and Watanabe 2017)</i>	0.276 – 0.670 (Extensive)
<i>(Banta 2018)</i>	0.317 (Extensive)
<i>(Shafique, Xue, and Luo 2020)</i>	0.34 - 9.82 (Extensive and intensive)
<i>(Fan et al. 2020)</i>	11.4 - 12.8 (Intensive)

- Cost

Setting up of a Green Roof requires a significant initial investment. Vijayaraghavan has documented and summarized in their paper the findings of various scientists and researchers who have tried to calculate the initial cost of creating a Green Roof as well as performed the cost benefit analysis. The results have varied because of different factors such as the type of Green Roof, the location, substrate and vegetation used, equipment used and the labor (Vijayaraghavan 2016). The initial cost is approximated to be \$129/ m²- \$161/m² for British Columbia and Canada (Bianchini and Hewage 2012), \$107.64/m²- \$161.46/m² for extensive Green Roofs in Chicago whereas it is \$161.46/m²- \$269.1/m² for intensive Green Roofs (Yang, Yu, and Gong 2008).

In an experiment conducted by Douglas and Jeremy in Ontario, Canada, the initial cost of Green Roofs is \$245/m² and \$188/m² after subsidy (Auld and Wright 2018), which is different from what has been mentioned above for Canada. For Chennai, India, the Green Roof cost varies between \$33.33/m² - \$55.5/m² (Vijayaraghavan 2016).

Though setting up of a Green Roof is expensive, there has been research where future cost savings have been calculated and incorporated to view an overall return on investment (ROI). Various factors are included such as energy saving costs, property appreciation value, air quality and carbon costs, which are still difficult to be included to their precise values. While some have proved the overall valuation to be positive (Rowe 2011)(Niu et al. 2010), others have presented contrasting results (Carter and Keeler 2008). Thus, this aspect needs further study and has not been fully considered in this thesis.

- Maintenance

Green Roofs require attention and care, especially during the first two years of their installation. Maintenance costs include irrigation costs, labor costs and a few other comparably smaller costs (such as removing seedlings). According to a Life Cycle Cost (LCA) assessment done in 2003 for Germany, USA, and Brazil, the annual maintenance cost is \$1/m² for extensive Green Roofs and \$8/m² for intensive Green Roofs (Porsche and Köhler 2003). The prices for the resources keep increasing, thus, a more recent study by Sproul in 2014 for the United States mentions the annual maintenance cost for the same situation as \$2.90/m² (Sproul et al. 2014). It is less expensive to maintain extensive Green Roofs than intensive Green Roofs (Porsche and Köhler 2003).

2.2.1.2 Vertical Green Systems / Vertical Gardens / Living Walls

Vegetation has often been used in architecture for exterior as well as interior walls for aesthetic purposes. Its first recorded use dates to 600BC, where the high stone terraced garden walls were covered with a variety of trees, shrubs and plants using an efficient irrigation system and known as the Hanging Gardens of Babylon (Cartwright 2018). Such use of landscape in a vertical direction is now termed as the Vertical Greenery System (VGS). They are “relatively light structures anchored on building facades with plants embedded on felt layers and nurtured by a hydroponic watering system” (Pulselli et al. 2014).

- Working Mechanism and Prerequisites

VGS has four main considerations - 1) Climate type 2) Plant species used 3) Construction System and 4) Mechanism of operation (Pérez et al. 2014).

Though, being a vertical element makes the implementation of vertical facades and walls difficult, it has been found from various studies that their effect is greater than Green Roofs due to the larger surface area of walls as compared to roofs. With increasing numbers of skyscrapers being constructed in the world, the surface area covered by the walls is approximately 20 times greater as compared to the roofs (Pérez et al. 2014).

There are several construction methods for VGS. Green facades have been classified into double-skin green façade, grid system, cable wire system, mesh system, whereas living/green walls have been classified into pocket system, geotextile felt system, modular system, and many others (Radić, Dodig, and Auer 2019). They all have a growing medium and a panel system (Figure 6), but the prerequisites as well as the working mechanisms differ for each construction method.

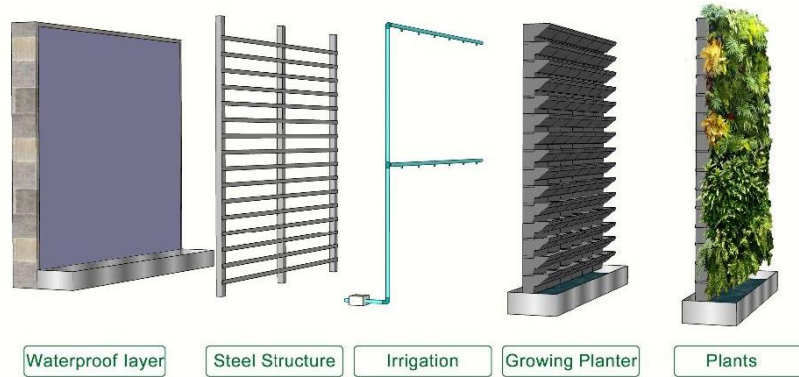


Figure 6. - Components of a typical Vertical Greenery System (VGS)
(Credit: Daniel Neyman)

- CS Potential

Vertical greenery system Carbon Sequestration and Living walls Carbon Sequestration were the phrases used for the search. Out of total 16 published papers, only 4 directly provided the CS potential values of VGS, excluding 1 literature review (Figure 7).

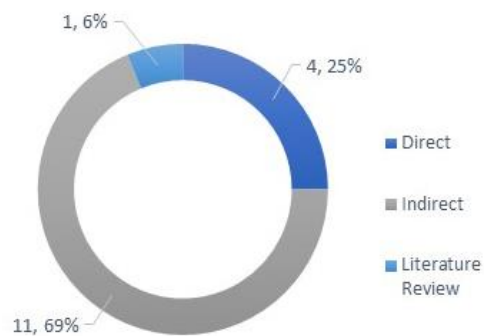


Figure 7 - Records determining the CS potential for Vertical Greenery System

Amongst the 4, two simulation-based studies dealt with the CS quantification by VGS. A life cycle assessment (LCA) of VGS was carried out in Italy as a part of a project named “GREENED.” A VGS installation was hypothesized on a 98m² facade for simulation. The results showed that plants used (herbaceous perennial) in VGS capture carbon from the

atmosphere at a rate of 250 g C/m² (Pulselli et al. 2014). Another simulation experiment was performed by Marchi in 2015. The carbon captured was in the range from 37.32 g C/m² - 270g C/m² with the average being 169 g C/m² approximately. A species of *S.nemorosa* also showed some exceptional CS potential in the range of 610 g C/m² - 4565.6 g C/m² (Marchi et al. 2015). Various CS potential values for VGS are shown in Table 3 below.

Table 3 - CS Potential values for Vertical Greenery System

<i>Reference</i>	<i>Annual CS Potential (kg C/m. sq.)</i>
<i>(Pulselli et al. 2014)</i>	0.247
<i>(Amir, Yeok, and Rahman 2014)</i>	0.253
<i>(Marchi et al. 2015)</i>	0.037 – 0.270
<i>(Charoenkit, Yiemwattana, and Rachapradit 2020)</i>	0.063 – 0.118

- Cost

A VGS consists of various components and has a considerable initial cost. According to Perini and Rosasco, who performed a Cost Benefit Analysis in 2013, \$41.1/m² – \$61.67/m² was the cost of direct greening system. With plants and supporting material it increases to a range of \$54.8/m² – \$102.75/m², with planter boxes, to \$205.5/ m², and even \$1097/m² for plastic material. For living walls, the cost varies between \$548/ m² - \$1644/m² (Perini and Rosasco 2013).

Rosasco in their paper calculates the initial cost for indirect green façade. One made with high density polyethylene (HDPE) costs around \$140/m², with steel mesh costs \$268.8/m²

and with planter boxes, it ranges from \$184.8/m² - \$369.6/m². The initial cost for living walls is \$207.2/m² - \$560/m² (Rosasco 2018). Similar results have been achieved in another study by Huang in 2019 (Huang et al. 2019).

- Maintenance

The maintenance requirements for VGS differ for each construction system. While for direct and indirect green facades, only pruning is required, planter box system additionally requires substitution of water tubes and plant species. Living walls also require a change of panels. Pruning is approximately \$3.84/m² annually, plant species replacement is \$1.9/m² – \$3.76/m² annually and annual panel replacement for living walls can cost up to \$8.28/m². Irrigation is required to be done annually at a rate of \$1.31/ m². There can be further other costs such as cladding renovation, irrigation system costs that might differ from case to case (Perini and Rosasco 2013).

2.2.1.3 Algae Curtains / Facades

Algae is often seen in a negative light due to its less aesthetically pleasing characteristics as compared to other plants, but it is considered to be an essential plant in the world since it generates approximately 50% of the total oxygen produced (Chapman 2013). For the same reason algae is being considered in recent years as a sustainable alternative to the predominantly used glazed facades to address climate change (Kyoung-Hee 2013).

- Working Mechanism and Prerequisites

Algae can be grown by two methods – open pond and closed system known as photobioreactor. While the open pond system is more economical, it faces a lot of

challenges in terms of external contaminants, whereas the photobioreactor prevents cross contamination by encapsulating algae in tubes (Kyoung-Hee 2013). The latter method is being used to integrate algae with structures in the form of facades and curtains. Algae utilize photosynthesis for CS. (Aouf 2018).

Algae curtains introduced by EcoLogic Studio are made up of 16 (2m by 7m long) bioplastic modules. It has embedded serpentine tubes which contain algae. When the unfiltered air enters the curtains from the bottom and start moving upwards, the micro-algae in the tubes capture CO₂, releasing O₂. They further grow biomass from the absorbed CO₂ (Aouf 2018) (Figure 8).



Figure 8 - Main façade of Printworks building at Dublin Castle presented in Climate Innovation Summit 2018

(Credit: ecoLogic Studio)

- CS Potential

The keywords used to determine the records measuring the CS potential of microalgae were, Microalgae Carbon Sequestration, Algae facades Carbon Sequestration and Algae CO₂ sequestration. It was found that out of total 28 published papers, only 7 directly provided the CS potential values of algae facades, excluding 2 literature reviews and 1 website which became the main source of information (Figure 9).

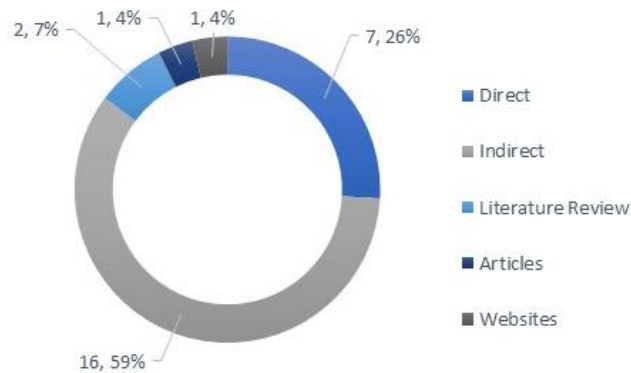


Figure 9 - Records determining the CS potential for Algae facades/curtains

According to a survey conducted by The Naval Research Lab in Washington, DC, an algae facade of 1.524m x 3.657m having 6.5 liters of algae solution can sequester around 2.43 kg C/m² (Kyoung-Hee 2013).

The algae curtain invented and displayed by EcoLogic Studio of 2 m² absorbs 1 kilogram of CO₂ every day, which is equivalent to the carbon sequestered by 20 large trees (Aouf 2018). When this is calculated in terms of amount of carbon sequestered annually gives a value of 2.970 kgC/m². The huge anomaly in variation that can be observed in the two cases mentioned might be due to varying amounts of algae solution used in the façade or the curtain.

The first house built using algae facades is in Hamburg, Germany. According to their estimation, algae facades can sequester 2.500 kg C/m² in a year (Colt International, Arup 2013). The value demonstrated by the BIQ house is closer to the value estimated by EcoLogic studio. Various CS potential values are shown in Table 4 below.

Table 4 - CS Potential values for algae facades/curtains

<i>Reference</i>	<i>Annual CS Potential (kg C/m. sq.)</i>
<i>(Colt International, Arup 2013)</i>	2.5
<i>(Kyoung-Hee 2013)</i>	2.43
<i>(ecoLogicStudio 2019)</i>	2.97

- Cost

Although algae can be found and grown easily, the costs associated with incorporating it in facades is not yet clear. There have been proposals and demonstrations of algae facades and curtains by globally influential architectural firms, for instance, HOK proposed an algae facade for the U.S. General Services Administration (GSA) retrofitted project in Los Angeles (Kim 2013), EcoLogic displayed a prototype of algae curtains in the Climate Innovation Summit 2018 in Dublin and also proposed an Algae Urban Farm in Tehran, Iran (Kim 2013). Evidence for the initial installation cost for this technique cannot be found easily on the available sources. BIQ house in Hamburg, Germany built in 2013, the first house to integrate an algae façade, (although not used with the objective of sequestering carbon) (Kim 2013) is the only project which indicates the cost of building an algae facade as \$2200-2300 /m² (Wilkinson et al. 2017). The cost is substantially high, but it is expected that with the rapid advancement of technology, prices may change to be more affordable.

- Maintenance

Several issues have been raised with respect to algae facades including maintenance issues such as cleaning of facades and algae carrying tubes, associated costs with continuous supply of water and nutrients to the algae façade as well as removal of the grown algae (Wilkinson et al. 2017). Odor, structural retrofitting, harmful toxins are some of the other issues related to it. While the issues are known, a clear description of the maintenance costs is not available.

2.3 Comparative Study

When all the published records between the years 2000 and 2020 (August) were analyzed, it was found that for Green Roofs most of the research was published during the later years starting from 2008. Resources for the CS potential of VGS were scarce, and almost all the published material was found 2013 onwards. Though, algae facades are often seen in a negative light, a significant amount of research has been carried out since 2000 to determine the CS potential of algae facades (Figure 10).

Search platforms: Scientific database (e.g. Scopus and the web of science)
 Search year range: 2000 – August 2020
 ● Number of papers from that year

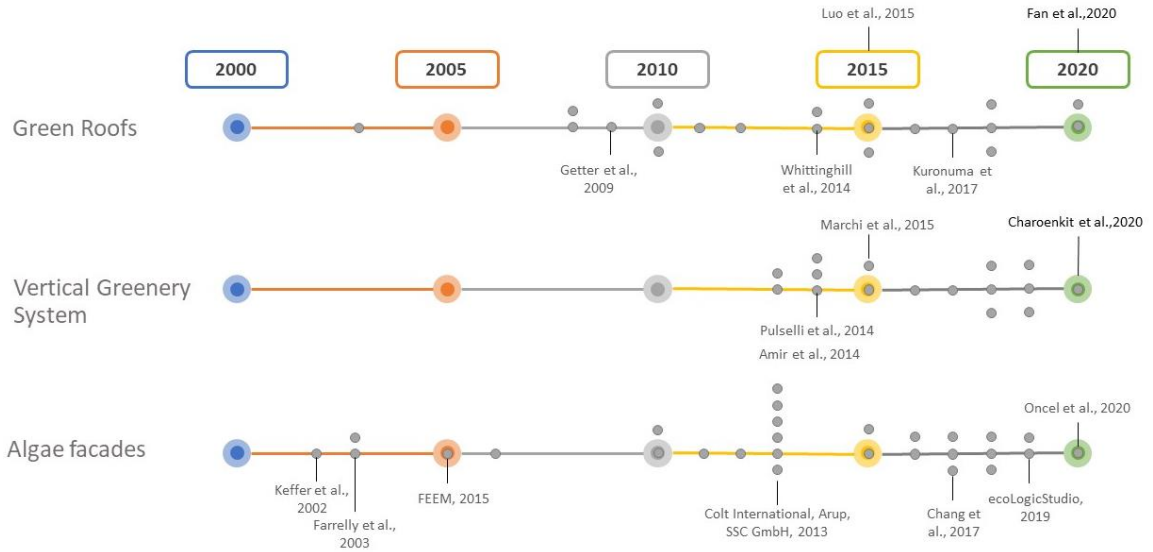


Figure 10 - Comparison of the time span of the published records for each biotic technique.

After a detailed literature review, the biotic techniques with respect to different design criteria – prerequisites, maintenance requirements and CS potential has been summarized in the table below (Table).

Table 5 - Summary of CS techniques based on the performance indicators (Biotic techniques)




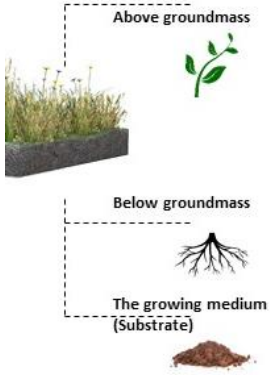
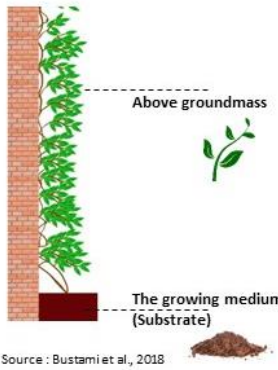




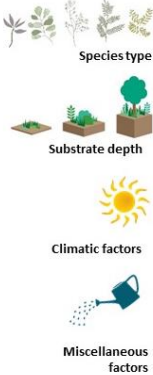
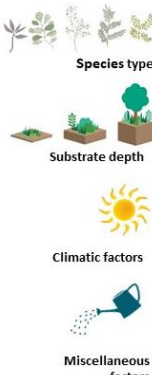
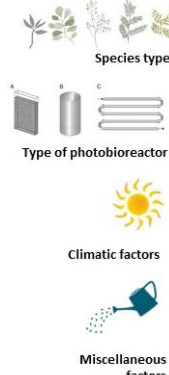
	<p>Green Roofs</p> 	<p>Vertical Greenery System (VGS)</p> 	<p>Algae Facades</p> 
CS Method	Photosynthesis	Photosynthesis	Photosynthesis
Types	Extensive Semi-intensive Intensive	<p><u>Green facades</u></p> <p>Double-skin green façade Grid system Cable wire system Mesh system</p> <p><u>Living/green walls</u></p> <p>Pocket system Geotextile felt system Modular system and many others</p>	Flat plate Annular Tubular
Components	Vegetation layer Growth substrate layer Filter layer Drainage Layer Protection mat Waterproof membrane Insulation Root barrier	Vegetation layer Growing planter layer Irrigation layer Steel structure Waterproof layer	Algae Medium inlet Water inlet Gas (CO ₂) inlet Water outlet Algae culture harvesting outlet
Components contributing to sequestering carbon	 <p>Above groundmass</p> <p>Below groundmass</p> <p>The growing medium (Substrate)</p>	 <p>Above groundmass</p> <p>The growing medium (Substrate)</p> <p>Source : Bustami et al., 2018</p>	 <p>Algae</p> <p>Source : ColtInternational</p>

Table 5 - Summary of CS techniques based on the performance indicators (Biotic techniques) Continued

	<p>Green Roofs</p> 	<p>Vertical Greenery System (VGS)</p> 	<p>Algae Facades</p> 
<p>Cost (Without normalization)</p>	<p>\$129/ m²-\$161/m² for British Columbia and Canada</p> <p>\$107.64/m²-\$161.46/m² (extensive), \$161.46/m²-\$269.1/m² (intensive) for Chicago</p> <p>\$33.33/m² - \$55.5/m² for India</p>	<p>\$207.2/m² - \$560/m² (Rosasco 2018)</p> <p>\$548/ m² - \$1644/m² (Perini and Rosasco 2013)</p>	<p>\$2200-2300 /m² (Wilkinson et al. 2017)</p>
<p>Major factors affecting the CS potential</p>			
<p>CS Potential</p>			
<p>Annual Carbon Sequestration range (kg C/m. sq.)</p>	<p>0.276 – 0.670 (Extensive Green Roof)</p>	<p>0.037 – 0.270</p>	<p>2.43 – 2.970</p>
<p>Average annual Carbon Sequestration</p>	<p>0.473</p>	<p>0.154</p>	<p>2.70</p>
<p>Tree equivalent of 100 m. sq. of the technique (Average carbon sequestered by 1 tree annually = 6.1 kg)</p>	<p>7.75</p>	<p>2.5</p>	<p>44</p>

2.4 Qualitative Literature Review

2.4.1 Materials

A considerable number of materials have been explored, tested and proven to capture carbon, such as alkaline earth metals, calcium and magnesium oxides (Huntzinger et al. 2009), biochar, solidia cement, titanium dioxide (Chawla 2018) (Ćurčić 2018). Titanium dioxide, biochar and various cements have been experimented widely within architecture in the form of photocatalytic facades and carbon-negative building materials.

Carbon-negative building materials are products with less than neutral carbon footprint. Such materials have an effect of removing CO₂ from the atmosphere (Chawla 2018). One of a similar working material is developed by Berlin based – Elegant embellishments. It uses biomass (organic waste) which absorbs and stores CO₂ (Ayoubi 2018).

- Working Mechanism and Prerequisites

Biomass is created by plants that absorb CO₂ and sunlight throughout its life. To make a carbon negative material, the process of pyrolysis is used to bake biomass to a stable form of carbon in an oxygen free environment. Further, it is mixed with a bio-degradable binder. This carbon negative material is then shaped into the products to be used in building facades and the interiors (Chawla 2018). Faceted panels have been created using this material for experimentation stage. ‘Charscraper’ is one of the first instances of a projection made from thermoplastic “Made of Air” – a carbon negative building material (Figure 11).

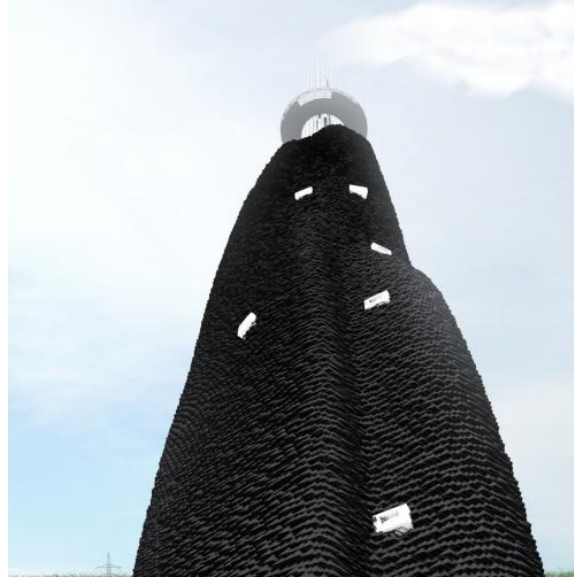


Figure 11 - Tower made using Made of air panels – Charscraper

(Credit: Elegant Embellishments)

- CS Potential

The amount of CS that has been approximated in the lab is based on the percentage of manufactured goods. It has been reported that if 10% of all manufactured goods in the construction industry are made up of the carbon negative material, it can capture up to 10^{15} gC annually from the atmosphere (Biddulph Jim 2017).

2.4.2 Equipment - Filter / Smog Absorbing Towers

Carbon emissions by vehicles, factories, construction industry have increased to such extreme levels that Direct Air Capture (DAC) is being considered and discussed largely throughout the world. One method of DAC is through equipment which can be integrated with structures. Dubai-based architectural studio Znera has proposed to create high rise towers with a grid of air filters (Page 2018). In Switzerland, carbon is being sucked directly

by a giant new machine developed by Climeworks (Marshall 2017). Also, Daan Roosegarde has been working on a smog free tower that is being known as the world's largest air purifier (Figure 12) (Verma 2015).



Figure 12 - The smog free tower by Daan Roosegarde.

(Credit: Studioroosegarde)

- Working Mechanism and Prerequisites

The smog project developed by the Znera Space has filtration pods at the bottom of the tower to capture pollutants from the air at a lower level where people breathe air and the propellers provided at the top circulate the clean air. To power the towers, hydrogen fuel cells along with solar panels are to be used. Carbon particles collected would then be converted into graphene, concrete and even ink (Page 2018).

The Dutch designer Daan Roosgaarde's works also depict similar concepts. It includes air filtering tower which absorbs carbon and creates diamonds by compressing the pollutant.

It claims to run on 1400 watts of green energy. A small positive current is used to send positive ions into the air through an electrode. These ions attach themselves to the fine dust particles which are then drawn towards the negatively charged surface. It allows the fine dust particles to collect and store inside the tower (*Dezeen* 2018).

The giant machine sequestering carbon in Switzerland uses a similar mechanism but it has a waste heat recovery facility that powers the entire machine. The filter system located underground collects CO₂ with the help of fans. CO₂ is occasionally separated at temperatures above 100⁰ Celsius when the filter is saturated.

- **CS Potential**

The Smog Free Tower created by Daan Roosegarde is 7-meter-tall and at the time of writing this thesis, is the only tower in development. It can provide 255.5 million m³ of clean air annually (Thompson 2016). Another installation by Berlin-based Green City Solutions, which is named “CityTree” is 13-foot by 10-foot tall and is made up of moss culture. It is claimed to capture carbon equivalent to 275 trees (Page 2018) in a year, which on conversion, taking carbon sequestered by 1 tree as 2.5 tons, is equal to 0.58 million m³C. The giant machine in Switzerland developed by Climeworks captures 0.5 million m³ of carbon which is equivalent to carbon emissions by 200 cars (Marshall 2017).

2.5 Summary

As was seen in the keyword search, CS techniques have been researched extensively in various disciplines, however, the state of the art lacks a significant amount of work when it comes to the integration of CS techniques in the built environment. With very little time

left for the humankind to prevent permanent climate change damages, it is imperative to build a database of building - integrated CS techniques and evaluate their impacts and consequences as early as possible. Thus, taking a step in that direction, after a systematic literature review, CS techniques were divided into three major categories – Biotic, Materials, and Equipment, further split into sub-categories. They were explored and analyzed on performance indicators like pre-requisites, initial and maintenance costs and CS potential. While a lot of published quantitative research could be found regarding the CS potential of biotic techniques, materials and equipment were seen as the emerging class of techniques calling for more demonstration projects as well as scientific published literature. Further, along with a realization to bring more awareness regarding these techniques, an indispensable need to facilitate the implementation of CS techniques in the built environment became evident from the lack of resources available for architects, designers and engineers to use as a reference. Thus, an initial foundational simulation workflow that could be utilized to make early design decisions regarding the CS techniques was worked upon in the following section.

CHAPTER 3. TOOL WORKFLOW – BIOTIC TECHNIQUES

3.1 Overview

After an extensive literature study, a workflow is created to accommodate the use of CS techniques with an application point of view. It also forms a foundation for any future tool development in context of integration of CS techniques with the built environment. While three categories of techniques were explored in this study, the workflow is limited to only the first one – Biotic techniques, for the following reasons:

- The materials and equipment categories were explored with a qualitative viewpoint since not enough quantitative scientific data was available online or could be procured through available sources at the time of writing this thesis.
- Each material and equipment has its own properties, mechanisms, factors affecting their working and CS potential. Due to the limited scope of the thesis, they could not be combined and are left as possible future research directions.

3.1.1 Scope and Limitations for the Tool's Workflow

- The workflow concentrates on location and area of the structures primarily.
- Various parameters which might have a significant effect on the CS potential are considered as a constant or have not been explored due to a constraint of scope.
- The methodology relies mainly on the weather data files (in EPW file format) which include general weather information based on the location's long-term climate pattern. Thus, solar radiation values and the present results might deviate with the changing climatic conditions. Most updated climate files should be used for accurate results.

- Approximate values such as Photosynthetically Active Radiation (PAR) being 50% of the total solar radiation and 1 kg of biomass fixing 1.8kg of carbon for simplified calculations.
- A linear relationship is considered between the light energy and the biomass growth which is not true in every case. High intensity of light might lead to slow plant/algae growth.
- Photoinhibition, mutual shading and light attenuation are complex areas which were not included in this study.

3.2 Development Process

Proper planning is crucial for any software/tool development. There are 6 steps leading towards the development of this workflow (Figure 13).

1. Analysis and Planning
2. Requirements
3. Design and Prototyping
4. Script Development
5. Validation
6. Maintenance and Updates

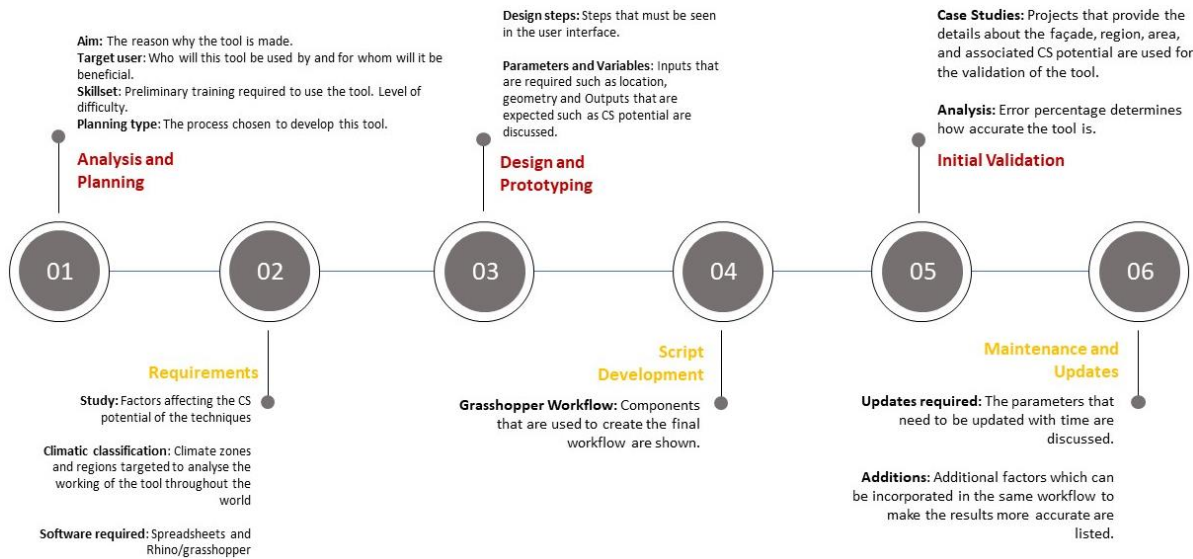


Figure 13 - Development process flow for the tool workflow

3.2.1 Analysis and Planning

3.2.1.1 Aim

With a rapid increase in the awareness and acceptance regarding the existence of climate change and its upcoming consequences, more focus is being laid down upon ways to cycle carbon effectively. Hence, the time is not far when our structures will have to accommodate CS techniques to absorb carbon directly from the atmosphere. With very limited knowledge about these techniques, architects might face a state of confusion while making decisions regarding the application of these methods. Hence, this workflow aims to facilitate that transition, and to enable architects in choosing and applying these CS techniques on their structures. It will allow them to make decisions in the early design stage by getting answers for questions like: “Which technique will perform better in a particular region?,” “Which orientation should be preferred for the technique?,” “How much carbon will their structure absorb after the application of the CS technique?,” and more.

3.2.1.2 Target User

An educated user related to the construction and design of a structure which can include an architect, a sustainability/high performance building consultant and a structural/civil engineer can use this tool workflow.

3.2.1.3 Skillset Required

A beginner level understanding of 3D CAD modelling in Rhino and visual scripting in Grasshopper is required to use this workflow. It is easy to use by following the instructions that are laid out properly at each step.

3.2.1.4 Planning Type

The planning was done in linear sequential phases which is known as waterfall planning. Moreover, various approaches were adopted to reach a final workflow which is termed as incremental and iterative planning in software development (Huemer, Lops, and Lopes 2012). Hence, waterfall in combination with incremental and iterative planning type was used for this workflow.

3.2.2 *Requirements*

Apart from the literature study already conducted in previous sections of the research, a more detailed study was required to decide the criteria that would determine the CS potential of the techniques. Hence, it was important to go through all the factors and their mechanism that affect the amount of carbon captured by a method after their application

on a structure along with some miscellaneous study like climate classification which can help in the wide adoption of the workflow.

3.2.2.1 Factors Affecting the CS Potential

All plants including unicellular organisms called microalgae use photosynthesis to capture carbon dioxide (CO₂) from the atmosphere (Getter et al. 2009) (Lehmuskero, Skogen Chauton, and Boström 2018). Photosynthesis is a biochemical process of converting light energy to chemical energy. During this process, the captured sunlight is used to convert water, CO₂ and minerals into oxygen and biomass (energy-rich organic compounds) (Lambers and Bassham 2020). Thus, as mentioned in the literature study, various factors such as species type, climatic factors, substrate depth/photobioreactor design and various other miscellaneous factors affect the photosynthesis process in turn affecting the potential of these biotic techniques to absorb carbon. Based on the differences and similarities in the techniques, the factors have been specified separately for the two groups – Green Roofs/Vertical Greenery Systems and Algae facades/curtains. It is also mentioned which factors will be considered a variable or a constant for the purpose of inclusion in the tool workflow.

- Green Roofs/VGS

The factors affecting the Carbon Sequestration for Green Roofs have been laid out in a research by Wan et al, 2019 (Wan Ismail, Abdullah, and Che-Ani 2019) after conducting a detailed literature study. The factors considered in the tool workflow are summarized in Table 6. The parameters varying in the workflow are highlighted in red/underlined (in case of a black and white print), while the constant parameters

are shown in bold black. Other parameters are not considered or explored or have been left to the discretion of the product manufacturer.

1. Location and position – Solar radiation/sunlight is the major factor for the process of photosynthesis. It consists of ultraviolet (UV) light, visible light (360nm – 720nm), and infrared light. Only light which can be used for photosynthesis is close to the wavelength range of the visible light and is known as the PAR. It is approximately 50% of the total radiation (Przyborski 2003). Out of the total PAR, plants can convert only a small amount of light energy into biomass which is represented by their photosynthetic ‘energy conversion’ efficiency (PE) or Energy Conversion Ratio (ECR). The theoretical maximum of PE for C3 plants is 4.6% and for C4 plants is 6% , while the real observed values have been between 1% - 2% (Zhu, Long, and Ort 2008). Solar radiation varies with every location in the world, the orientation of the building as well as the building element where the plants are placed, affecting their CS potential (J. Li et al. 2010). Thus, this factor has been explored and kept as a variable for the workflow. Also, since sedum mostly adopts Crassulacean Acid Metabolism (CAM) pathway (a specialized mode of photosynthesis where CO₂ is absorbed during the night time (Niechayev, Pereira, and Cushman 2019)), which is closer to C4 photosynthesis in terms of ECR, the minimum of the lower value i.e. 1% ECR is considered for the workflow.
2. Species of plants/trees – Various experiments have been carried out to conclude that different species of plants and trees sequester varying

amounts of carbon. Every plant/tree has a different diameter, density (Nowak et al. 2013), and leaf area index (LAI) (Gratani, Varone, and Bonito 2016). It has been found that trees can absorb a greater amount of CO₂ as compared to shrubs/grasses. Since extensive Green Roofs are considered for this study which cannot bear the weight of large plants or trees (Elkink 2017), species have been limited to grasses and shrubs. Sedum species, a succulent grass type, is specified for Green Roofs, it being the most common and easy maintenance grass for Green Roofs/VGS (Vijayaraghavan 2016).

3. Temperature – It affects plant growth at the physiological and biochemical level (Song et al. 2014), however, its quantified effect on the CS potential of Green Roofs couldn't be found in the literature studied for this research. Hence, this factor is not included in the workflow.
4. Precipitation – Since drought-resistant species, sedum is chosen for Green Roofs and VGS, this factor is not included.
5. Age – There have been contradicting views about the age affecting the CS potential of plants. While some studies show that older trees have a higher ability to store more carbon, others show the opposite (Banta 2018) (Wan Ismail, Abdullah, and Che-Ani 2019). Until and unless a detailed quantification and analysis of this factor is not conducted, age cannot be included in this workflow.
6. Substrate depth – Extensive Green Roofs have a substrate depth between 7.5cm and 15cm, while intensive Green Roofs have a substrate depth of

greater than 15cm (Elkink 2017). Since carbon is sequestered by the soil too, greater substrate depths result into more carbon being absorbed from the atmosphere (Getter et al. 2009). For the purpose of avoiding complexity and considering the popularity of the type, this study has been limited to extensive Green Roofs. Thus, the substrate depth is a constant factor fixed at substrate depth of 7.5cm -15cm.

7. Substrate composition – Substrate forms a major part of the system for Carbon Sequestration by plants. A study conducted to determine the amount of carbon captured by different substrate types like sewage sludge and natural soil concluded that the composition of substrate does affect the CS potential (Luo et al. 2015). For this study, natural soil substrate has been considered.
8. Area/No. of plants – A number of studies show that the area of a green coverage and the amount of carbon sequestered by them have a linear relationship (Wan Ismail, Abdullah, and Che-Ani 2019). Hence, area is considered as a variable parameter in this workflow.
9. Miscellaneous factors – Various other factors such as irrigation, fertilization, pruning and mowing can affect the growth of plants which further affect the carbon sequestered by them (Kuronuma and Watanabe 2017)(Wan Ismail, Abdullah, and Che-Ani 2019). These have not been included in this workflow and are considered future research directions.

Table 6 - Factors affecting the CS Potential (Green Roof/ Vertical Greenery System)

Technique	Research Paper	Factors affecting the algae growth (CS Potential)	Factors considered in the workflow
Green Roofs And Vertical Greenery Systems	Getter et.al, 2009	Species of plants (mechanism C3, C4, CAM)	Sedum – CAM (Constant)
	Kuronuma and Watanabe, 2016	Temperature	Not explored
	Banta, 2018	Precipitation	Not considered since species is sedum (requires less/no water)
	Shafique et al., 2020	Age (Green Roof)	Not considered yet
	Charoenkit et al, 2020	Substrate depth (Green Roof)	Extensive roofs - less than 15cm (Constant)
		Illuminance/solar radiation	<u>Solar radiation – varied based on location</u>
		Substrate composition	Natural soil (Constant)
		Area/ No. of plants	<u>Area of the facade/roof (Varied based on geometry)</u>

- Algae facades/curtains

The factors which affect the CS potential and are considered in the tool workflow are summarized in Table 7. The parameters varying in the workflow are highlighted in red/underlined (in case of a black and white print), while the constant parameters are shown in bold black. Other parameters are not been considered or explored or have been left to the discretion of the product manufacturer.

1. Sunlight/Solar radiation – Similar to plants, microalgae can also utilize only PAR for photosynthesis. The growth rate of microalgae is almost double or triple as compared to the plants due to their simple cell structure. Thus, their photosynthetic efficiency is also higher (Xu et al. 2019) with an ECR of 8% - 10% (Ng et al. 2015). Since, this is the theoretical maximum value, the

lower value i.e. 8% is considered for this workflow. Based on the case studies, this value can be brought down later to the most observed value.

The microalgae growth is also affected by the light and dark photoperiod ratios (Singh and Singh 2015), which is taken care of in the workflow with the help of the linear relationship between the amount of available solar radiation absorbed and the biomass produced.

2. Species of microalgae – There are about 200 – 800 existing species of microalgae, however, only 30 have been analyzed to date. Out of these green algae are the most efficient (M. Kumar et al. 2018). Properties of different species might differ, thus, chlorella vulgaris and spirulina being the most common species for experiments and industrial use, have been considered for this workflow (Krienitz, Huss, and Bock 2015).
3. Temperature – While light and temperature are closely related, temperature independently has a strong effect on the uptake of nutrients and CO₂ by microalgae. The cellular chemical composition as well as the growth rates are also affected by the same. For the workflow, optimum temperature of 20⁰C – 30⁰C is assumed to be maintained by the photobioreactor manufacturers (Singh and Singh 2015).
4. Initial concentration of microalgae – Lag phase is one of the various phases that occur during the microalgae growth which is affected by the initial concentration of microalgae. Thus, an optimum initial concentration value of 0.07 dw(dry weight) g/L is assumed in the microalgae solution along with the nutrients (Vasumathi, Premalatha, and Subramanian 2012). Since, the

workflow uses the light energy to estimate the biomass productivity, the concentration of algae cells is not further explored here.

5. Nutrients – Algae growth is influenced by the amount of CO₂ provided and SO_x and NO_x in the flue gas (K. Kumar et al. 2011). This has been considered to be maintained at an optimum amount by the photobioreactor manufacturers. Hence, not considered in the workflow.
6. Surface area/Volume ratio of photobioreactor – Photobioreactors are preferred over the open pond system because of a higher microalgae cultivation due to higher ratio of surface area to volume ratio and low contamination risks (Oncel, Kose, and Oncel 2020). Further in photobioreactors, for increased microalgae productivity, even distribution of light is found to be necessary. Various experiments and attempts have been made to provide direct and evenly distributed light in photobioreactors. Low light penetration and photoinhibition are some other challenges during algae growth (Kumar et al. 2011). Thus, to avoid complexity in the workflow at this stage, only direct sun light is considered for the biomass growth which depends solely on the area exposed that is decided by the owner/designer of the structure. Volume can be incorporated in the later stages of this workflow. For validation purpose, 0.01m thickness will be used, if and when required.
7. Design of the photobioreactor – Various types of photobioreactors exist, most common for industrial use being flat-plate, tubular and cylindrical. Flat plate photobioreactors being the most widely used, have a smaller light

path and greater exposed surface area leading to higher microalgae productivity (Vasumathi, Premalatha, and Subramanian 2012). Hence, they have been considered for this workflow.

8. Miscellaneous factors – Various other factors such as the method of harvesting algae and operation modes affect the biomass productivity (Oncel, Kose, and Oncel 2020). The centrifugal method has been considered for this workflow, since various studies showcase that it has one of the highest harvesting efficiencies (Japar, Azis, and Takriff 2017).

Table 7 - Factors affecting the CS potential (Algae facades/curtains)

Technique	Research Paper	Factors affecting the algae growth (CS Potential)	Factors considered in the workflow
Microalgae	Olaizola, 2003	Availability of carbon dioxide	CS Potential
	Vasumathi et al, 2012	Number of photons	<u>Solar radiation – varied based on location</u>
	Singh, 2015	Species of microalgae	Chlorella Vulgaris (constant)
	Gonçalves et al, 2016	Initial concentration of microalgae	Constant
	Farreira et.al, 2017	Nutrients	Nutrients (constant)
	Oncel et al., 2020	surface area/volume ratio of photobioreactor	<u>Area of the facade (Varied based on geometry)</u>
		Design of the photobioreactor	Flat plate photobioreactor (constant)
		Method for harvesting	Centrifugal – being the most common one (constant)

3.2.2.2 Classification of Climate Zones

In order to ensure that the workflow can be adopted in any part of the world and to find out the range of carbon captured using the CS techniques, the workflow is tested in various climatic regions throughout the world. According to Koppen classification, five climate zones have been identified – Tropical, Dry, Moderate, Continental and Polar (Kottek et al. 2006) as shown in Figure 14. From each zone, one country has been randomly identified whose location data can be fed into the workflow as an input. The countries with their associated climate zones are as follows: Tropical – Singapore, Dry – Australia (Sydney), Moderate – Atlanta, Continental – Canada (Toronto) and Polar – Antarctica (San Martin).

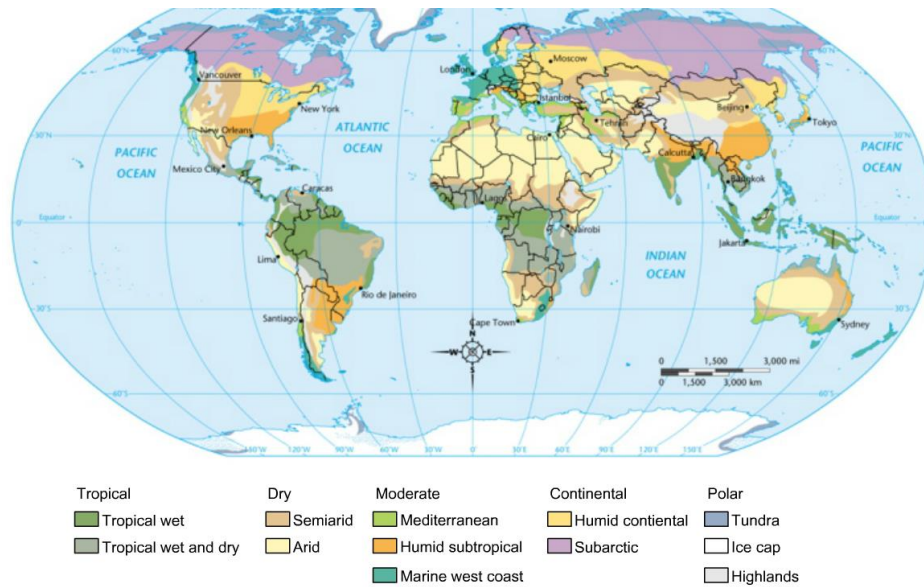


Figure 14 - Climate classification

(Credit: (Kottek et al. 2006))

3.2.3 *Design and Prototyping*

3.2.3.1 User Interface

The intent of the study to make the process of transitioning easier for the user and being able to apply the CS techniques in the simplest way possible. Thus, there are just four steps incorporated in the user interface to estimate the amount of carbon absorbed by the structure (Figure 15).

STEP 1: Select the location.

This step will help input the EPW file which will determine the solar radiation of the region where the structure is to be constructed.

STEP 2: Input/Create the Geometry.

In the initial stage, two options have been provided to input the geometry, first, to input the geometry in Rhino as a boundary representation (Brep), second, create a rectangular geometry (shoe box model) using length, width, height and the orientation of the building. Further window-to-wall ratio can be customized along with the overhangs on the windows. Curved/free form geometry can be included easily in further iterations of the workflow.

STEP 3: Select the CS technique to be applied on each building element.

There can be multiple possibilities when it comes to the application of techniques. The user might want to try different combinations of techniques on different buildings elements to get the desired output. Thus, an option to choose the CS technique for three separate buildings element categories – roof, wall/façade and windows has been provided.

STEP 4: Select the building elements where the technique has to be applied.

Finally, when the technique has been finalized, the user must choose the orientation of the building element (N, NE, E, SE, S, SW, W, NW) since each orientation and total area of the building elements will affect the CS potential.

These four steps provide the final approximate value of total carbon sequestered by the entire structure after applying the available CS techniques.

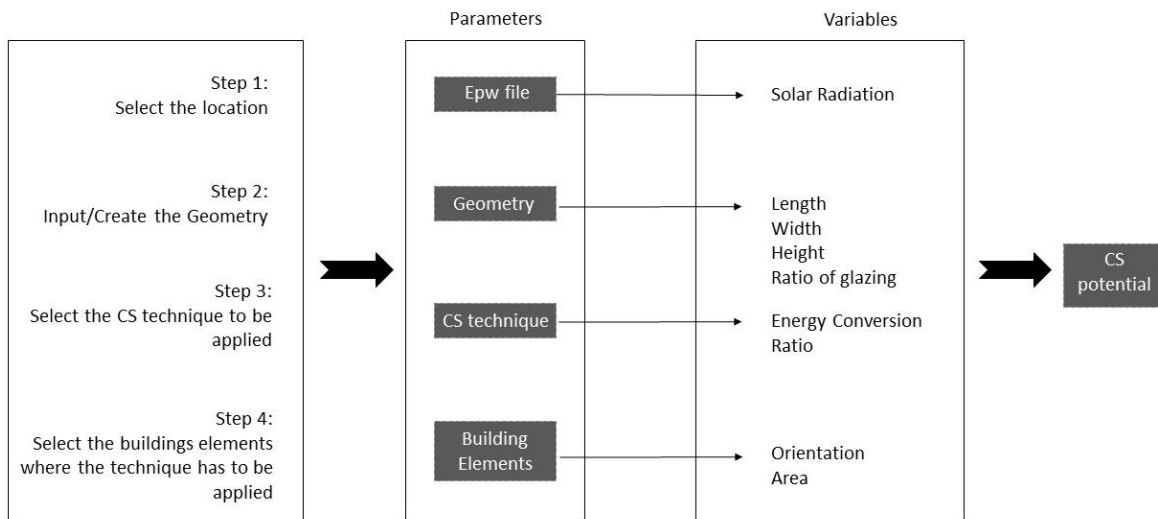


Figure 15 - User Interface

3.2.3.2 Engine

While the user interface is intended to be made simple, there are technical calculations and assumptions that form the simulation engine. They are explained as follows (Figure 16):

Engine step 1: To determine the location the EPW file is put in on the local drive.

Engine step 2: Solar radiation is determined from the inputs in kWh. It is the total radiation (direct +diffuse).

Engine step 3: Since photosynthesis requires only visible light known as the PAR (as previously mentioned) which is approximately 50% of the total radiation, the solar radiation is multiplied by 0.5.

Engine step 4: Out of the PAR, plants can absorb only a portion of it which is determined by their photosynthetic energy conversion efficiency (PE) or energy conversion ratio (ECR). The ECR is determined only when a particular CS technique is chosen. If Green Roof/VGS is chosen, PAR is multiplied by 0.3 (ECR average for plants) and if algae facades is chosen, PAR is multiplied by 0.8 (ECR for microalgae) to determine the light energy (E) absorbed to be converted to biomass per sq. m. in an year.

Engine step 5: Once the technique is chosen, the building elements and their respective orientation are chosen for the application of the technique. This helps in determining and calculating the total area (A) for each technique in meters squared (sq. m).

Engine step 6: The light energy absorbed (E) is multiplied by the total area (A) to determine the total energy absorbed (TE) that can be converted to biomass. Its unit is kWh/year.

Engine step 7: According to the calorific value for algae (*Chlorella vulgaris* and *Spirulina*) and plants, 1 g of dry weight of biomass can be harvested from around 21kJ (Chen and Torii 2015) and 15.55kJ – 18kJ of light energy respectively. Thus, using this conversion (from kJ to kWh) the amount of biomass produced (B) is determined by dividing the TE

by a factor of 0.0058 and 0.0043 and further dividing it by 1000 to change the unit from g to kg.

Engine step 8: Approximately 1 kg of biomass fixes 1.8kg of CO₂ (Adamczyk, Lasek, and Skawińska 2016). Thus, to calculate the amount of CO₂ sequestered by the structure in a year, total biomass (B) in kg is multiplied by a factor of 1.8.

Engine step 9: Further conversions are done to determine the CO₂ sequestered in a day and finally the carbon (C) sequestered by the structure in a day is calculated using the molecular mass of C by multiplying the amount of CO₂ sequestered

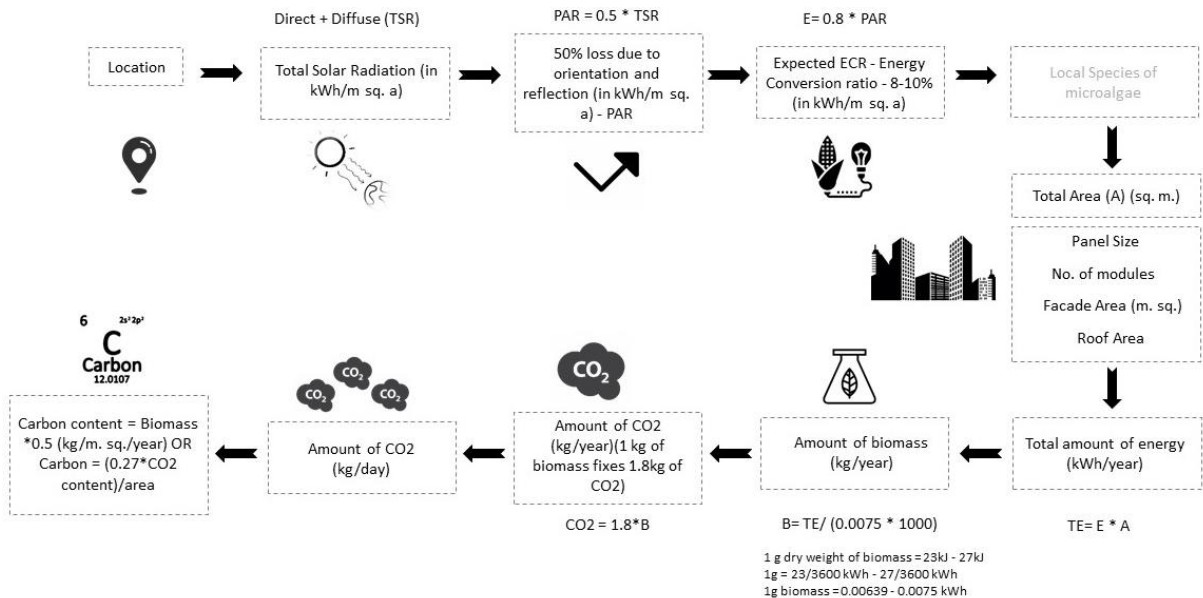


Figure 16 - Engine workflow

3.2.4 *Script Development*

The workflow is a parametric script in a visual programming interface – Grasshopper. The interface consists of ladybug components (Roudsari and Pak 2013) to get the weather file for a location (Figure 17), set choices for CS techniques for each building element category (Figure 18), and create/input the geometry (Figure 19).

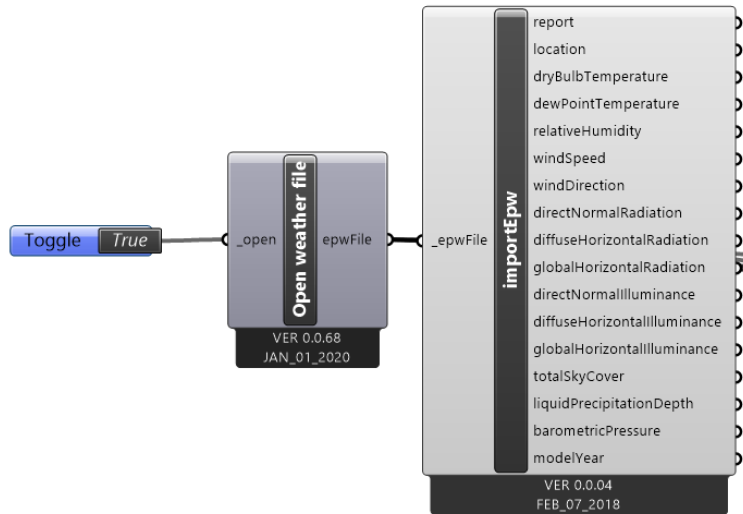


Figure 17 - Setting up the location

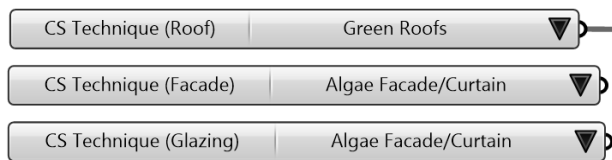


Figure 18 - Set the choices

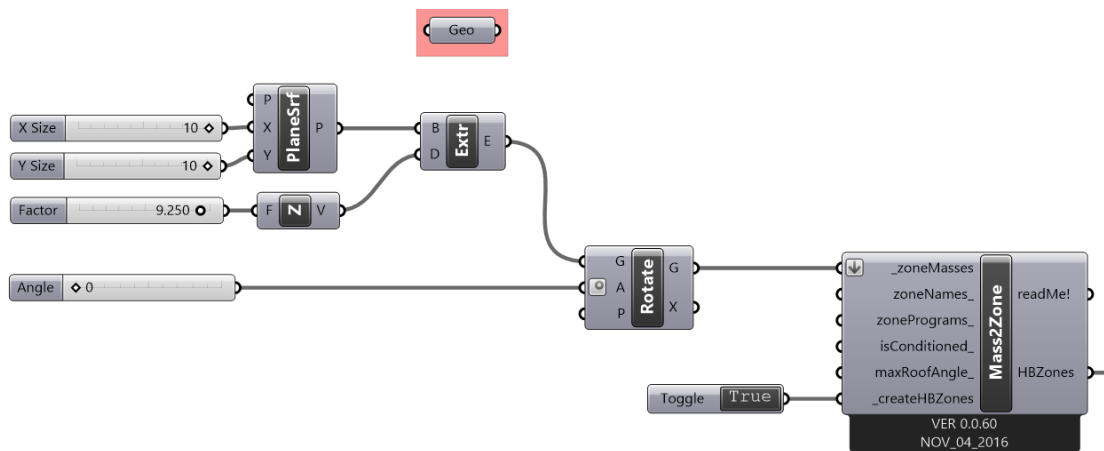


Figure 19 - Create/Input the geometry

Further the script includes defining the glazing ratios for the geometry (Figure 20), selection of the orientation of the building elements and creating grid points on them (Figure 21).

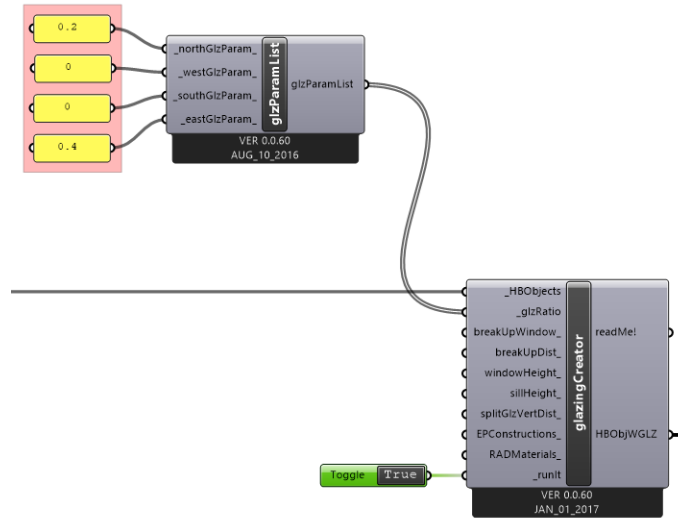


Figure 20 - Defining the glazing ratios

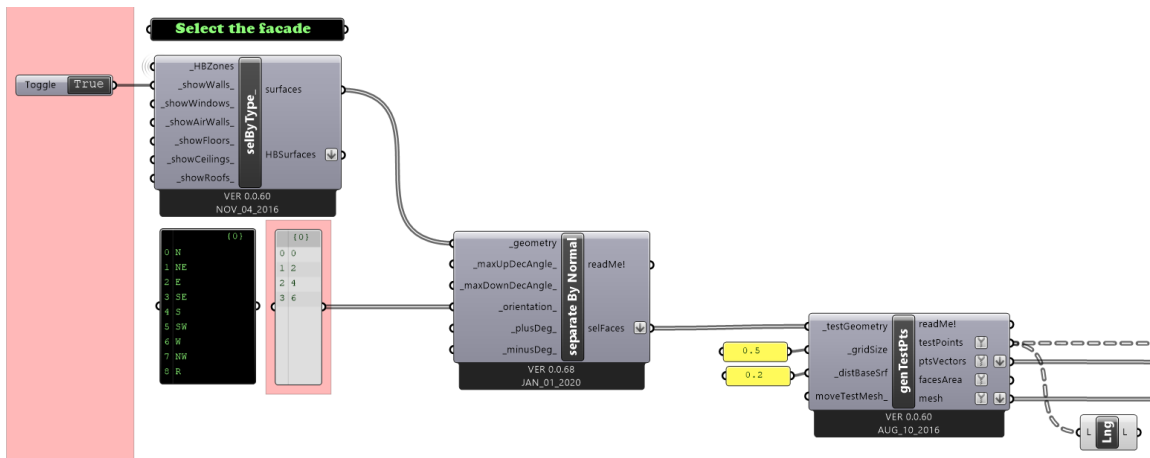


Figure 21 - Selecting the orientation of the building elements and creating their grid points

Finally, by using an analysis recipe, a cumulative sky model and calculations covered in the engine section, solar radiation and PAR is calculated (Figure 22) along with the area of the building elements to determine the carbon sequestered by the structure (Figure 23).

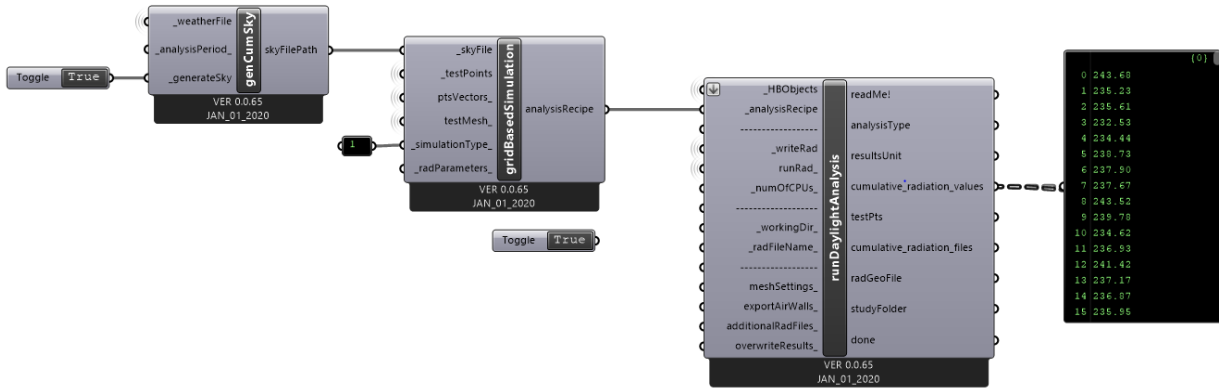


Figure 22 - Using analysis recipe and cumulative sky model to determine solar radiation

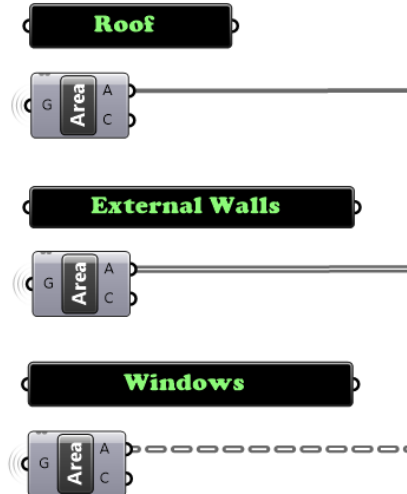


Figure 23 - Calculating the area of the selected building elements

3.2.5 *Initial Validation*

In order to check the extent of accuracy of the workflow, a number of case studies and published records are selected separately for Green Roofs/vertical greenery systems and algae facades. The percentage error is calculated in either the amount of CO₂ or carbon sequestered after the application of the technique.

3.2.5.1 Validation for Green Roofs/VGS

A. Case Study 1 (Green Roofs) – (*K. Getter et al. 2009*)

Getter et al. quantified the carbon sequestered by extensive Green Roofs with sedum species in Michigan as well as in Maryland. Varying amounts of CS potential was found in their results; however, they calculated an average which is used for the comparison of results in this section. Majority of the roofs were in Michigan, hence that location is chosen for the workflow. This study is one of the most important and detailed studies that have been conducted till now and have been considered as a basis for many who tried the same afterwards.

Table 8 - Comparison of workflow results with Case Study 1 (Green Roofs)

	(K. Getter et al. 2009)	Workflow
Location	Michigan, USA	EPW file of Michigan (Lansing)
Solar Radiation for the chosen building element (kWh)	-	1379.58
Light energy equivalent of Photosynthetically Active Radiation (PAR)	-	689.79
Energy Conversion Rate (ECR)/Photosynthetic efficiency (PE)		0.5% (Changed from 1%)
Area of the facade	-	-
Biomass produced (kg/m. sq./year)	-	0.8
Carbon dioxide sequestered (kg CO ₂ /m. sq./annum)	-	1.44
Carbon sequestered (kg CO₂/m. sq./annum)	0.375	0.389 (0.779 for ECR = 1%)

Table 8 shows the comparison of results of the case study and the workflow developed in this study. A 3.73% error has been found between the experimental and specified case values for the carbon sequestered which is within an acceptable range, however, this was achieved when the ECR value was changed from 1% to 0.5%. This might provide an insight that plants absorb much less carbon than expected. Moreover, the CS potential amount is higher in the workflow, which might be due to the lack of contextual buildings which usually decreases the solar radiation amount falling directly on the plants, hence justifying the error.

B. Case Study 2 (Green Roofs) - (Kuronuma et al. 2018)

A study was conducted by Kuronuma and his colleagues to estimate the amount of carbon sequestered by three grass species and one sedum species since these are the most common

plants for a Green Roof. An extensive Green Roof with a substrate depth of 5cm was considered. Irrigation was provided for the grass species while sedum species were tested in both irrigated and non-irrigated conditions, which has not been considered in the workflow.

Table 9 - Comparison of workflow results with Case Study 2 (Green Roofs)

	(Kuronuma et al. 2018)	Workflow
Location	Center for Environment, Health and Field Sciences at Chiba University, Japan	Epw file of Tokyo, Hyakuri, Japan (33km from Chiba)
Solar Radiation for the chosen building element (kWh)	-	1289.74
Light energy equivalent of Photosynthetically Active Radiation (PAR)	-	644.87
Energy Conversion Rate (ECR)/Photosynthetic efficiency (PE)		0.6% (1%)
Area of the roof	-	-
Biomass produced (kg/m. sq./year)	-	1.59
Carbon dioxide sequestered (kg CO₂/m. sq./annum)	Sedum →1.68 (Grass species → 2.5)	1.62 (2.69)

Table 9 shows the comparison of results of the case study and the workflow developed in this study. The percentage error of 3.5% for sedum species with an ECR of 0.6% again emphasizes the inferences from the previous case study that plants absorb less carbon. Also, here with grass species absorbing higher carbon dioxide from the atmosphere than the sedum species, it can be concluded that while ECR for sedum species is 0.5% - 0.6%, grass species have a higher ECR of 0.9% - 1%. Thus, various species with their respective ECRs can be added into the workflow providing the user an option to choose them.

C. Case Study 3 (VGS) - (Pulselli et al. 2014)

A hypothetical vertical wall of 98m² was considered, and carbon sequestered by the wall was quantified. This was based on another model created using STELLA software. The simulating model takes in account all the stages in the life cycle of the plants on a vertical green wall (Marchi et al. 2015). The plant species chosen were perennial herbaceous plants, which included sedum, perennial grass, herbaceous shrubs, and ornamental flowering plants.

Table 10 - Comparison of workflow results with Case Study 3 (VGS)

	(Pulselli et al. 2014)	Workflow
Location	Mediterranean climate (probably Italy, Tuscan)	Epw file of Pisa (in Tuscany), Italy
Solar Radiation for the chosen building element (kWh)	-	1135.34
Light energy equivalent of Photosynthetically Active Radiation (PAR)	-	567.67
Energy Conversion Rate (ECR)/Photosynthetic efficiency (PE)	-	0.5% (Changed from 1%)
Area of the façade (m ²)	98	78.4 (Taking glazing ratio as 0.2 approx.)
Orientation of the facade	South	South
Biomass produced (kg/year)	-	51.75
Carbon dioxide sequestered (kg CO ₂ /annum)	90	93.15 (186.30 for ECR = 1%)

Table 10 shows the comparison of results of the case study and the workflow developed in this study. The percentage error of 3.5 with the ECR of 0.5% further strengthen the fact assumed in the previous two studies.

D. Case Study 4 (VGS) - (Amir, Yeok, and Rahman 2014)

A legume species was grown on a wall, which is 2.5m wide and 3.67m high. LICOR – 3000A and 3050A were used to investigate the Carbon Sequestration potential of the plants on the wall.

Table 11 - Comparison of workflow results with Case Study 4 (VGS)

	(Amir et al. 2014)	Workflow
Location	Tropical climate (Malaysia)	Epw file of Penang, Malaysia (George Town)
Solar Radiation for the chosen building element (kWh)	-	653.4
Light energy equivalent of Photosynthetically Active Radiation (PAR)	-	326.7
Energy Conversion Rate (ECR)/Photosynthetic efficiency (PE)	-	0.7% (Changed from 1%)
Area of the façade (m ²)	9.175	9.175
Orientation of the facade	-	South
Biomass produced (kg/m. sq./year)	-	0.53
Carbon dioxide sequestered (kg CO ₂ /m. sq./annum)	0.935	0.957 (1.367)

Table 11 shows the comparison of results of the case study and the workflow developed in this study. A percentage error of 2.3 with an ECR of 0.7% shows that the legume species has higher photosynthetic efficiency as compared to the sedum species but lesser than the expected 1%.

3.2.5.2 Validation for Algae Facades/Curtains

Three case studies are chosen for algae facades/curtains.

A. Case Study 5 - BIQ House

BIQ house in Hamburg, Germany (Figure 24), is the world's first and the only live project featuring the bio-reactive algae façade panels (FEEM 2015). These flat-plate algae photobioreactors are called Solarleaf, and each panel is 2.5m x 0.7m with a depth of 80mm (Wurm and Pauli 2016). There are 129 panels put up on the southeast and southwest façade of the house and are filled with fluid consisting of nutrients to cultivate microalgae (IBA_Hamburg 2013).



Figure 24 - The BIQ (Bio Intelligent Quotient) House by Arup, Hamburg, Germany.
(Credits: inhabitat.com)

With an area of 185m² and an 8% energy conversion rate (ECR) for microalgae to convert the light energy to biomass, the BIQ house was expected to produce 900kg of biomass per

year. It was estimated to sequester 2.5 tons of CO₂ per year (FEEM 2015). After the first monitoring results, it was found that the biomass produced was down to 600kg per year, bringing ECR down to 4.4%.

Table 12 - Comparison of workflow results with Case Study 5 (Algae facade)

	BIQ House	Workflow
Size (m ²)	Plot size: 839 Gross floor area: 1600 (IBA_Hamburg 2013)	Area per floor: 340 approx. (Considering 4 floors and a 5 th smaller one too) – 18.5 x 18.5
Location	Hamburg, Germany	EPW file of Hamburg, Germany
Solar Radiation	-	-
Light energy equivalent of Photosynthetically Active Radiation (PAR)	-	-
Energy Conversion Rate (ECR)/Photosynthetic efficiency (PE)	8%	8%
Area of the facade	185	185
Orientation of the facade	Southeast Southwest	Southeast Southwest
Biomass produced (kg)	900	1450
Carbon dioxide sequestered (kg CO ₂ /annum)	2500 (Colt International, Arup 2013)	2610

Table 12 shows the comparison of results of the case study and the workflow developed in this study. A 4.4% error was recorded between the experimental and specified case values for the CO₂ sequestered, which is within an acceptable range. However, there is some significant difference in the amount of biomass produced, which should be further investigated. After monitoring the results of the BIQ house, it was found that the biomass productivity was lower than expected, leading to an ECR of 4.4%, although technical

difficulties were mentioned as the reason. With more years of monitoring, a final real value for the ECR will probably be monitored.

B. Case Study 6 - PhotoSynthetica by Ecologic Studio

Algae containing curtains have been manufactured by a London based firm called Ecologic studio. Photo.Synth.Etica, a carbon-negative product, is made to be used as a cladding on the building façade to absorb carbon dioxide from the atmosphere (Figure 25). Its first demonstration has been on the Printworks façade in the Climate Innovation Summit 2018 (ecoLogicStudio 2019).

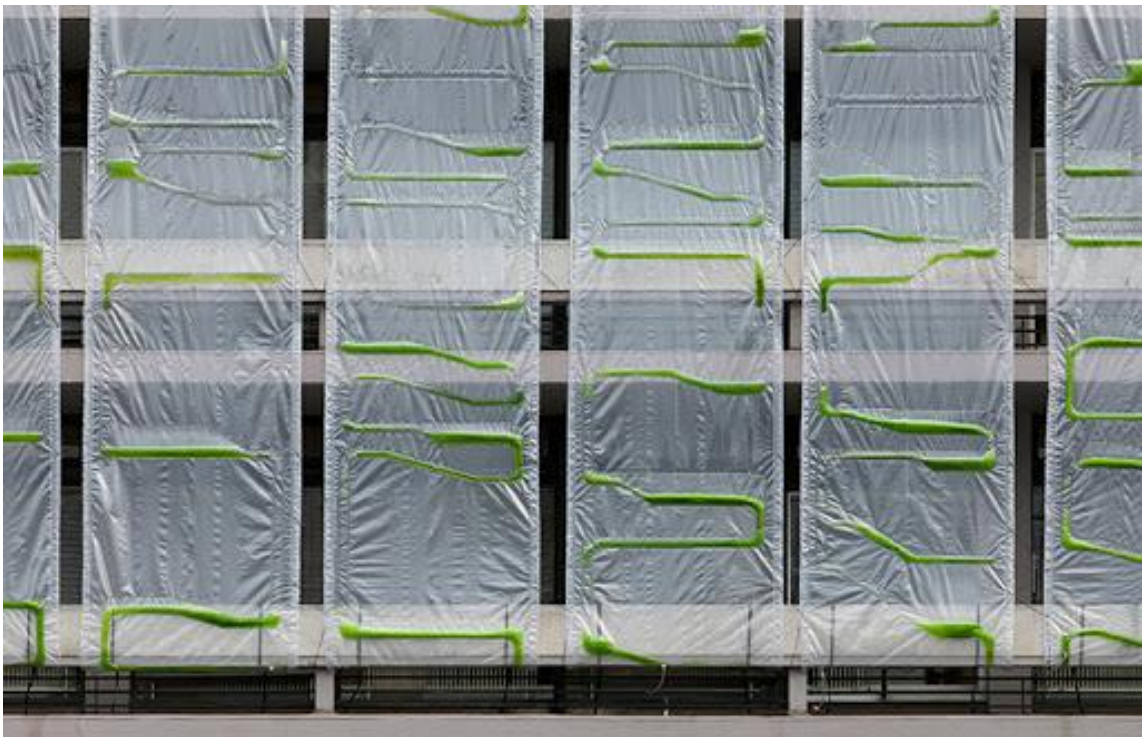


Figure 25 - Photo.Synth.Etica by Ecologic Studio
(Credits: Ecologic Studio)

Table 13 - Comparison of workflow results with Case Study 6 (Algae facade)

	Photosynthetica	Workflow
Location	Dublin, Ireland	Epw file of Dublin, Ireland
Solar Radiation	-	710.43
Light energy equivalent of Photosynthetically Active Radiation (PAR)	-	355.2
Energy Conversion Rate (ECR)/Photosynthetic efficiency (PE)	8%	8%
Area of the façade (m ²)	224 (ecoLogicStudio 2019)	224
Orientation of the facade		South
Biomass produced (kg)	-	-
Carbon dioxide sequestered (kg CO ₂ /m. sq./annum)	11	8.8

Table 13 shows the comparison of results of the case study and the workflow developed in this study. A 20% error difference between the workflow and the specified case study value is recorded, which is at the higher end of an acceptable margin of error. This could be due to a number of factors:

- The curtain has tubular algae photobioreactors, while this workflow is meant for a flat plate photobioreactor.
- The amount of algae and biomass produced is not exactly known.
- Since the value claimed is not from a scientific source, but from the online website of the product, there might be an error in the claimed value.

C. Case Study 7 - (Keffer and Kleinheinz 2002)

An experiment was conducted in the lab using two fluorescent lamps 15m apart to estimate the CO₂ bio fixation.

Table 14 - Comparison of workflow results with Case Study 7 (Algae facade)

	(Keffer and Kleinheinz 2002)	Workflow
Location	Lab: Cool white, fluorescent lighting (Average sunlight equivalent – 2.4×10^{19} – 3.0×10^{19} photons/s/m ²)	Epw file of Chicago (Since it gets average sunlight hours)
Solar Radiation (kWh)	-	952.47
Light energy equivalent of Photosynthetically Active Radiation (PAR) (kWh)	-	476.43
Energy Conversion Rate (ECR)/Photosynthetic efficiency (PE)	-	4% (8%)
Biomass produced (kg)	-	3.28
Carbon dioxide sequestered (kg CO ₂ /m. sq./annum)	5.5 (Converted from 63.9 g/m ³ /h and assuming the thickness to be 0.01m)	5.911 (11.82)

Table 14 shows the comparison of results of the case study and the workflow developed in this study. A percentage error of 7.4 with an ECR of 4% shows that the CS potential of microalgae might be lower than the ideal design value that aligns with the real values found in the BIQ house. This might also be a case due to the use of fluorescent lamps instead of sunlight. The lab results have often indicated a lower microalgae productivity.

3.2.6 *Maintenance and Updates*

The workflow developed is an initial stage script which will require regular updates and maintenance for improved performance and future workability. There can be a number of additions that can be made easily to the workflow with future developments. They are as follows.

- Addition of CS techniques – Currently, only biotic techniques have been included in the workflow. While the materials and equipment category would not depend on the same factors as the biotic techniques, their workflow can be made easily following the same planning.
- Adding more factors to the workflow – A number of factors such as temperature, species, and precipitation have been left unexplored in this workflow. With more research, they can be added. For example, various species of plants/microalgae can have different PE/ECR values. They can be added as a choice for the user or automatically shortlisted on the basis of the location. Their amount of biomass can also be calculated directly using the Leaf Area Index (LAI), the diameter of the tree, and the density. In doing so, a relationship between solar radiation and the amount of biomass in the species will have to be established.
- Geometry – The workflow is limited to a cuboidal shoebox analysis or any input geometry. Freeform geometry governed by coordinates can be included in the workflow. Moreover, similar to overhangs, many more building elements can be incorporated into the workflow.

- PE/ECR – The PE/ECR value must be updated with advanced real-time project results to acquire more accurate Carbon Sequestration values.
- Cost – Financial aspects are often difficult to be included in a workflow since it fluctuates with regions as well as time. However, if the costs of all the techniques are normalized, they should be incorporated in the later stages of the workflow.

CHAPTER 4. RESULTS, CONCLUSIONS, AND DISCUSSION

4.1 Results

The results have been divided into three sections. The first one provides the inferences from the literature review. The second section provides the final workflow after its validation. The third one provides the range of carbon sequestered in different locations identified, on façade orientations and different type of geometry based on the updated workflow.

4.1.1 Inferences from the Literature Review

Based on the literature review, it is observed that Green Roofs and VGS capture carbon in the range of $150\text{gC/m}^2 - 650\text{gC/m}^2$, while algae facades perform better and sequester up to around $2430\text{gC/m}^2 - 2970\text{gC/m}^2$. They all require an initial investment, but there is a possibility that their future benefits overcome the initial cost. Carbon captured by materials is dependent on the percentage of products using those materials, whereas equipment could absorb a high amount of approximately $687.5 \times 10^6\text{gC} - 250.65 \times 10^9\text{gC}$ without normalization, but it is significantly expensive.

It is not possible to normalize both materials and equipment without further understanding of the system; for instance, the ability to capture carbon by filter towers is not proportional to the size of the equipment, as is the case with Green Roofs, VGS, algae facades. Therefore, Figure 26 focuses only on visualizing biotic potentials, with the aim to aid in the quantification of CS potential. Cost is shown with dashed lines to signify its subjectiveness (not normalized).

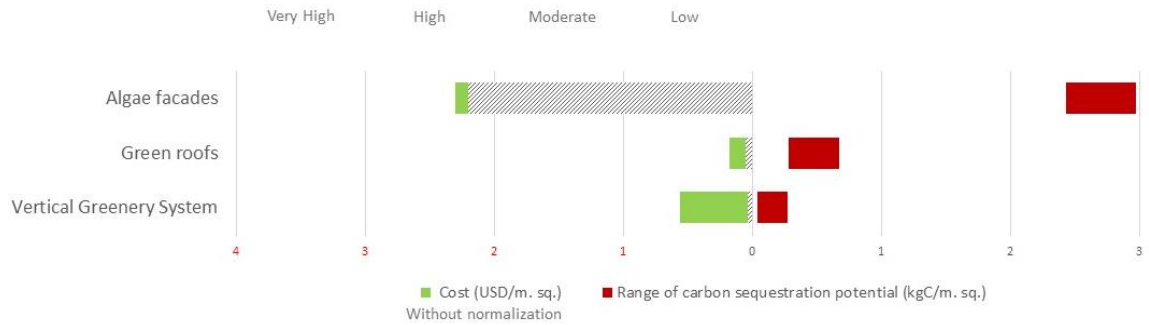


Figure 26 - Comparison of CS potential and cost for biotic techniques.

4.1.2 Updated Tool Workflow

There were 4 case studies considered for Green Roofs and VGS – 2 for each. All of those emphasized that the PE/ECR for plants (sedum) is much lower than expected and should be 0.05%. Thus, the workflow is updated with that value. Moreover, with a lower percentage error, it was seen that the workflow could be used to predict the amount of carbon sequestered by the Green Roofs/VGS when applied to a structure.

In the case of algae facades/curtains, while the estimated values from the first case study (BIQ house) matched the estimated CS potential (whether 8% or 4.4% is considered), the second case study values had a higher percentage error indicating the need for more information to predict the reason for the error range. The third case study, which was conducted in a lab, indicated lower values of ECR. Thus, relying on the results from the monitored values of BIQ house and the third case study, the workflow was updated with an ECR of 4%, specifying that it is the minimum amount of CO₂ that can be sequestered after the application of the technique.

4.1.3 CS potential values for different climatic zones

The updated workflow was used to estimate the carbon sequestered in various climate regions as specified in one of the previous sections. A 25 m x 25m x 12m shoebox without any glazing was analysed for two scenarios – 1) Green roof and VGS on all facades, 2) Green roof and Algae façade on all facades. The two scenarios were compared to evaluate the CS potential and performance of each technique in every climatic region. The outputs for each climate zone are as follows.

- Tropical – Singapore (Figure 27)

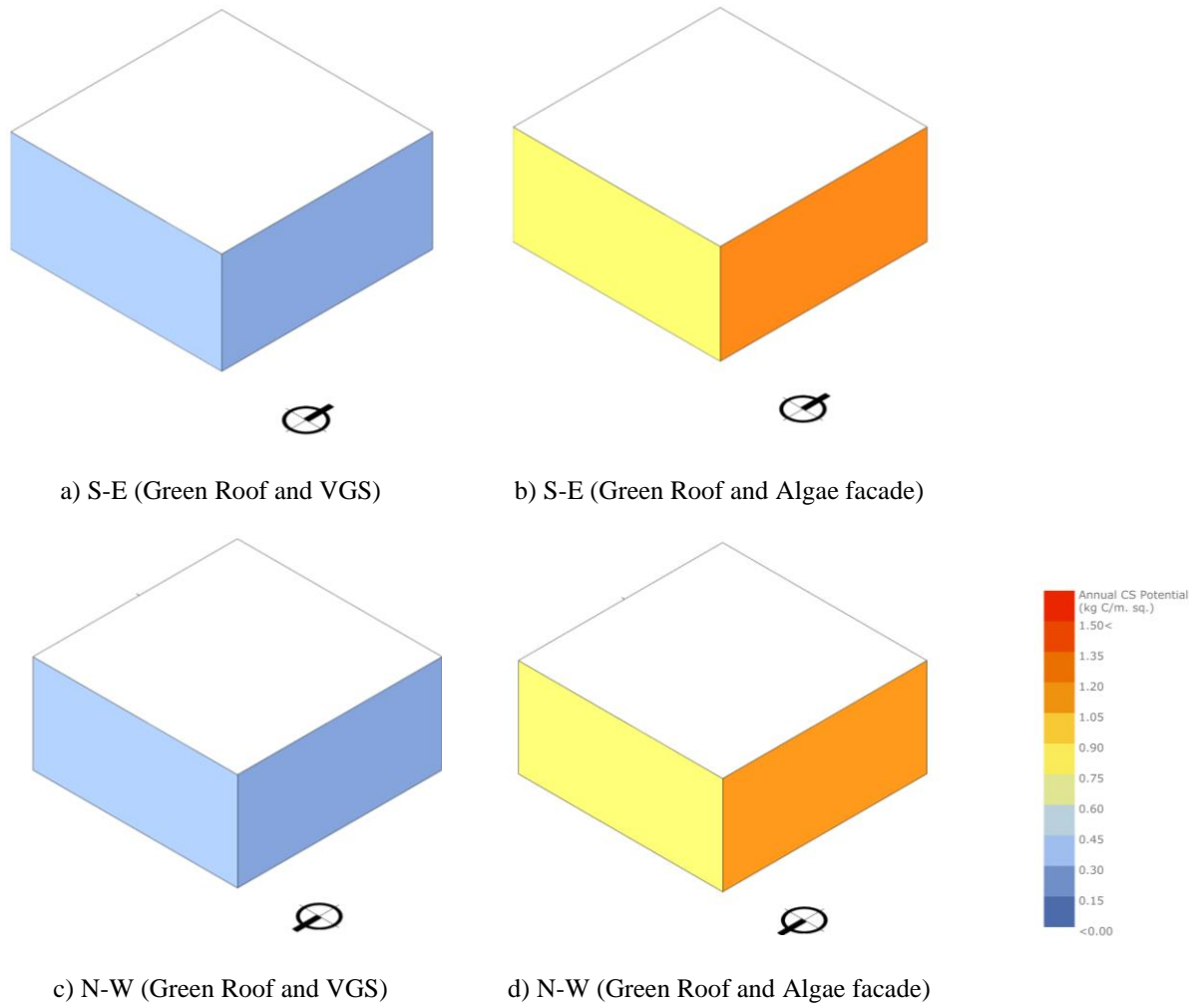


Figure 27 - CS Potential visualization result in tropical climatic region (Singapore)

For the tropical climate, eastern and western facades tend to perform better, thus, should be preferred for both VGS and Algae facades. The CS potential of algae facades fall between 0.93 kg C/m²/ annum – 1.2 kg C/m²/ annum. While VGS can only capture a minimal amount of carbon from 0.116 kg C/m²/ annum – 0.15 kg C/m²/ annum, Green Roof absorbs a moderate amount of around 0.467 kg C/m²/ annum (Table 15).

- Dry – Australia (Sydney) (Figure 28)

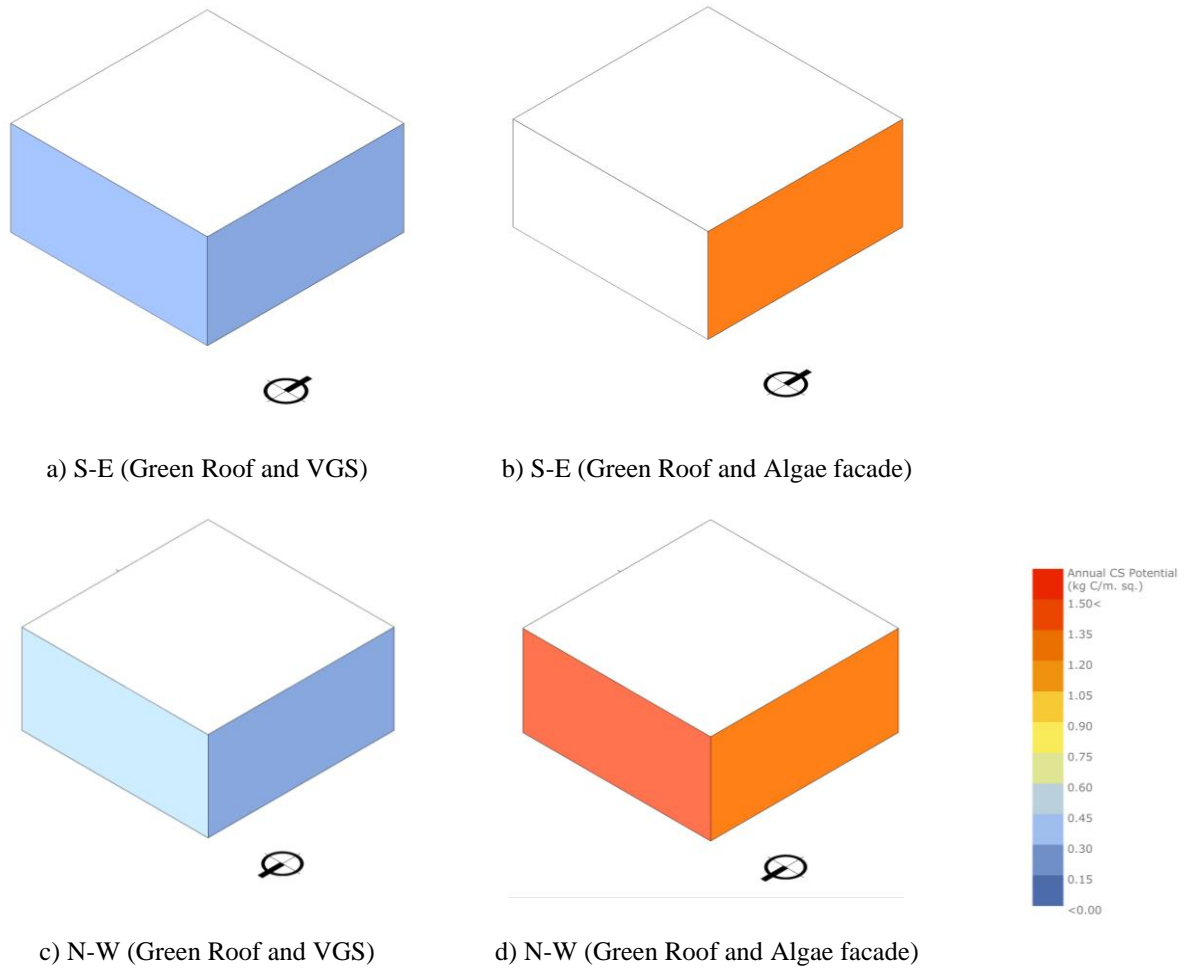


Figure 28 - CS Potential visualization result in dry climatic region (Australia)

For the dry climate, all facades except for the southern façade tend to perform well, thus, south facing wall should not be used for the application of VGS and Algae facades. Surprisingly, north facade captures the maximum amount of carbon. The CS potential of algae facades fall between 0.48 kg C/m²/ annum – 1.67 kg C/m²/ annum. While VGS can only capture a minimal amount of carbon from 0.06 kg C/m²/ annum – 0.21 kg C/m²/ annum, Green Roof absorbs a similar amount as the tropical climate of around 0.461 kg C/m²/ annum (Table 15).

- Moderate – Atlanta, USA (Figure 29)

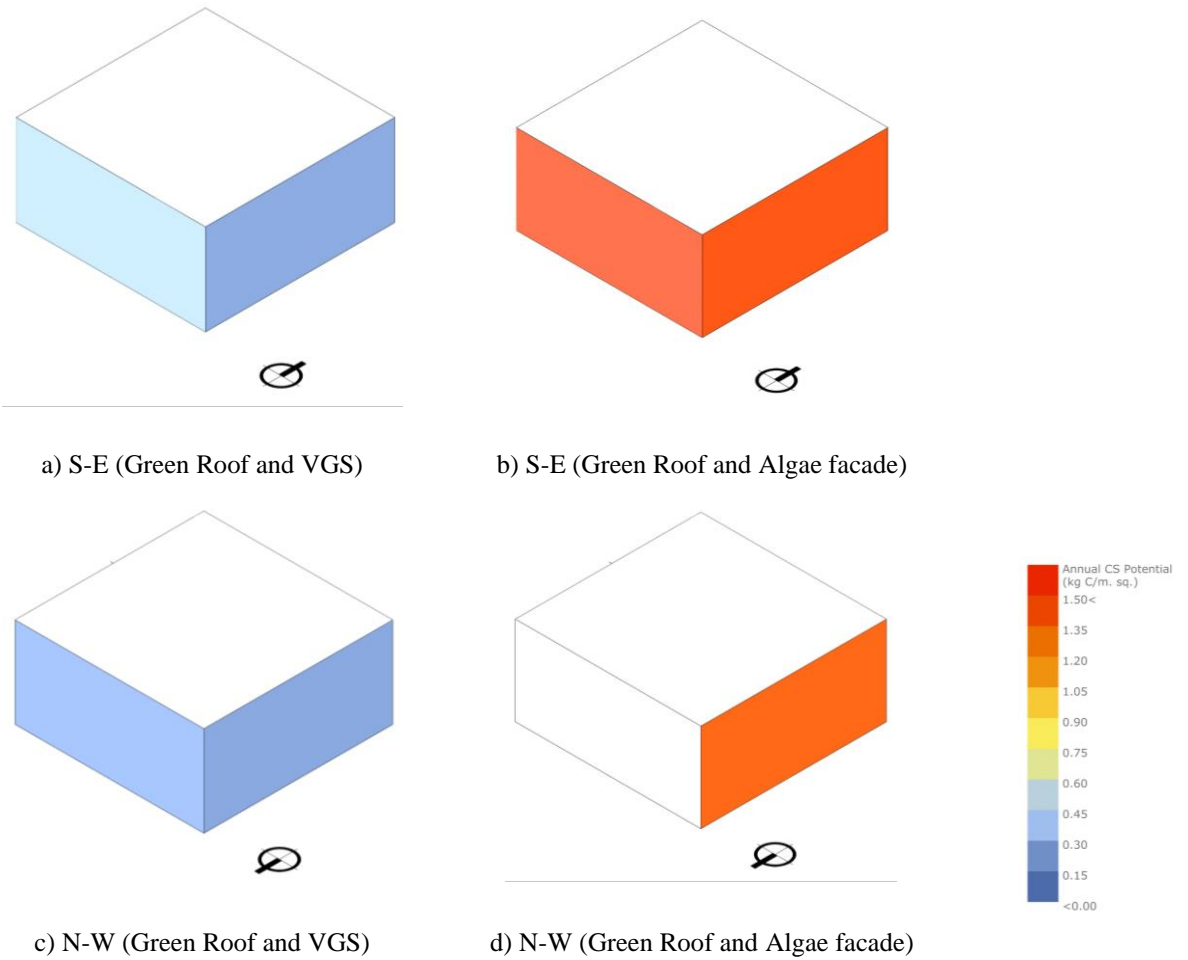


Figure 29 - CS Potential visualization result in moderate climatic region (Atlanta)

For the moderate climate, all facades except for the northern façade tend to perform well, thus, north facing wall should not be used for the application of VGS and Algae facades. Southern facade captures the maximum amount of carbon. The CS potential of algae facades fall between 0.5 kg C/m²/annum – 1.72 kg C/m²/annum absorbing slightly higher amounts of carbon as compared to previous climatic zones. VGS captures 0.06 kg C/m²/annum – 0.215 kg C/m²/annum. Green Roof absorbs a similar but slightly higher amount of carbon with 0.47 kg C/m²/annum (Table 15).

- Continental – Canada (Toronto) (Figure 30)

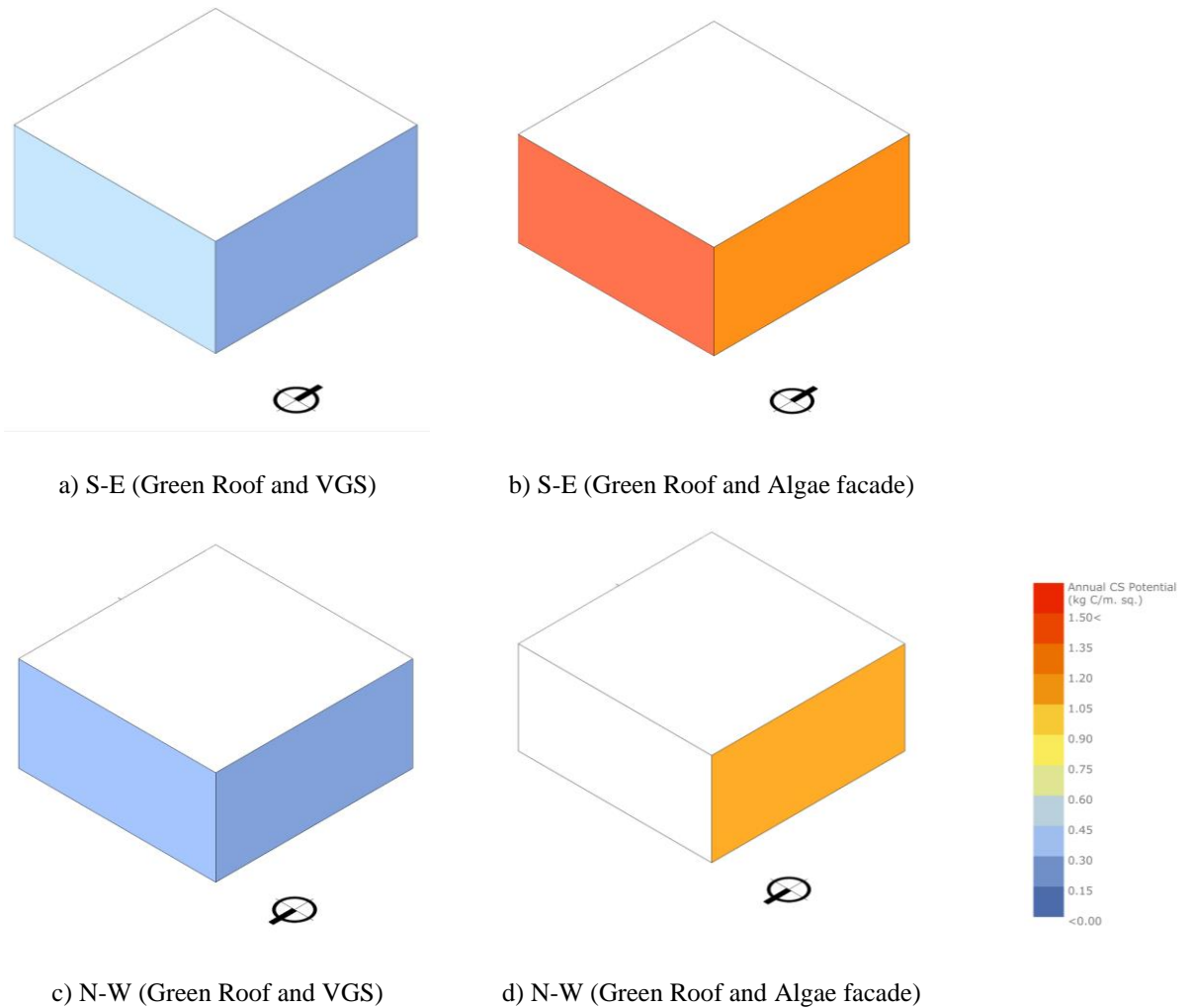


Figure 30 - CS Potential visualization result in continental climatic region (Canada)

For the continental climate, southern and eastern façade tend to perform better than the western façade, while northern has a much lesser CS potential. Southern facade captures the maximum amount of carbon. The CS potential of algae facades fall between 0.424 kg C/m²/annum – 1.51 kg C/m²/annum. VGS captures 0.053 kg C/m²/annum – 0.189 kg C/m²/annum. Green Roof does not perform that well in this climatic region as compared to the previous ones with 0.366 kg C/m²/annum (Table 15).

- Polar – Antarctica (San Martin) (Figure 31)

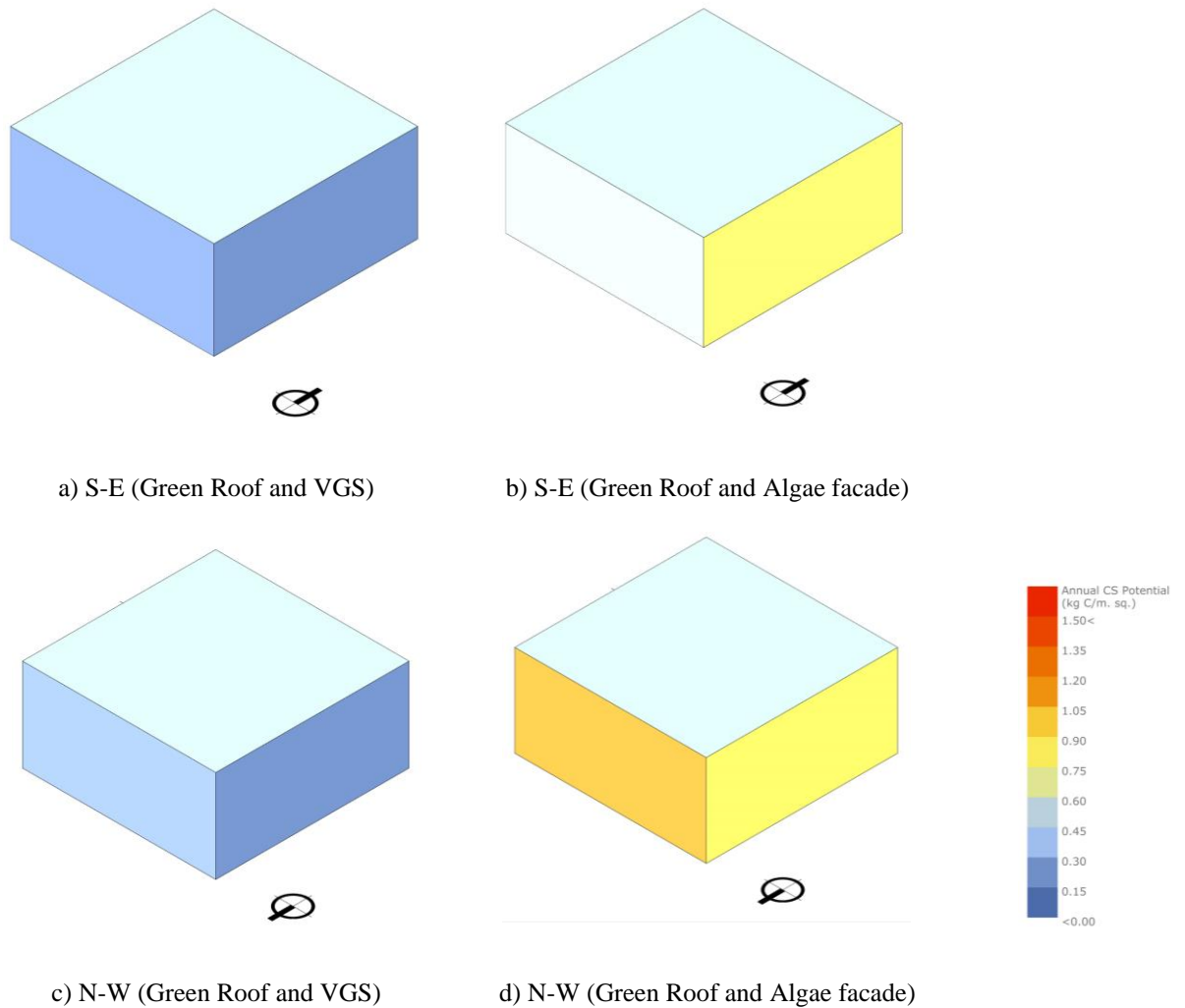


Figure 31 - CS Potential visualization result in polar climatic region (Antarctica)

For the polar climate, northern façade performs better than the eastern and the western façade, while southern façade having a much lesser CS potential. The CS potential of techniques is much lower in this climatic region when compared to other four mentioned above. Algae facades capture between $0.336 \text{ kg C/m}^2/\text{annum}$ – $1.114 \text{ kg C/m}^2/\text{annum}$. VGS captures $0.042 \text{ kg C/m}^2/\text{annum}$ – $0.14 \text{ kg C/m}^2/\text{annum}$. Green Roof does not perform that capture $0.218 \text{ kg C/m}^2/\text{annum}$ (Table 15).

Table 15 - CS Potential for different climatic zones

	Green Roofs (kg C/m. sq./ annum)	Vertical Greenery Systems (kg C/m. sq./ annum)				Algae façade/curtain (kg C/m. sq./ annum)			
		N	E	S	W	N	E	S	W
Tropical – Singapore	0.467	0.116	0.15	0.118	0.14	0.929	1.19	0.95	1.12
Dry – Australia (Sydney)	0.461	0.21	0.154	0.06	0.154	1.67	1.23	0.48	1.23
Moderate – Atlanta	0.47	0.06	0.172	0.215	0.163	0.498	1.375	1.72	1.30
Continental – Canada (Toronto)	0.366	0.053	0.147	0.189	0.13	0.424	1.174	1.51	1.04
Polar – Antarctica (San Martin)	0.218	0.14	0.09	0.042	0.095	1.114	0.714	0.336	0.757

The results in Table 15 show that the lowest amount of carbon was sequestered in the polar climatic region, which was expected due to the least amount of solar radiation there. While all the techniques are performing best in the moderate climate, it's interesting to notice that Green Roofs perform better in tropical regions as compared to the VGS and algae facades, which have a higher carbon sequestered in the dry region. This can be attributed to the difference in the sun angle in both the climatic regions.

4.2 Discussion and Conclusion

According to the IPCC, the minimum amount of CO₂ to be removed from the atmosphere by 2100 to avert the devastating effects of climate change is 100 gigatons (2.72 x 10¹⁴ g C) (Zhou 2018). In order to achieve this, apart from including more vegetation and biotic in the built environment, CS techniques need to be adopted. This study has provided an overview and a comparative analysis of all the building-integrated CS techniques to allow architects and designers to evaluate these technologies, analyze their integration potential in architectural practice based on prerequisites and cost, and make schematic design decisions. After a systematic literature study, it can be clearly seen CS techniques, which can be of biotic, materials, or equipment category, can sequester carbon in an effective way. On comparison of biotic techniques, Green Roofs and VGS can sequester an almost equal amount of carbon with Green Roofs being a little higher, keeping in mind only the extensive Green Roofs. Algae facades can sequester about six times more carbon than the other two techniques. CS potential of materials as well as equipment needs more detailed quantitative research as and when the experimental results are made available by the manufacturers of these products. Moreover, the expenses related to these techniques, both initial and maintenance, need to be normalized to get an accurate sense of their affordability and further bring them down for wider adoption.

With very limited time left to mitigate climate change, architects and designers must start making schematic design decisions to incorporate CS techniques. The tool workflow presented in this paper may assist with this. The simple approach adopted in the workflow can be impactful, as validated by a number of case studies. However, there is a significant scope to improve and update with factors not considered currently for more accurate

results. The simulation workflow has been designed for universal use catering to different climatic regions in the world. Thus, the designers can choose at an initial stage which technique works best for their region. Various other areas of discussion such as life cycle assessment of each technique in terms of cost, embodied carbon and benefits and implementation of these techniques on regulatory and policy level must be worked upon.

In conclusion, an overview was presented along with an initial stage of simulation tool workflow, however, advances in building-integrated CS techniques and more demonstrated projects along with continuous monitoring are needed in order for buildings to not just limit the catastrophic effects of climate change but also mitigate it for a better future for our built environment.

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