Final Thesis Defense Meeting – 11/11/2020

Building-integrated Biotic Carbon Sequestration Techniques : Overview and Simulation Workflow

Georgia Tech
High Performance Building Lab
College of Design

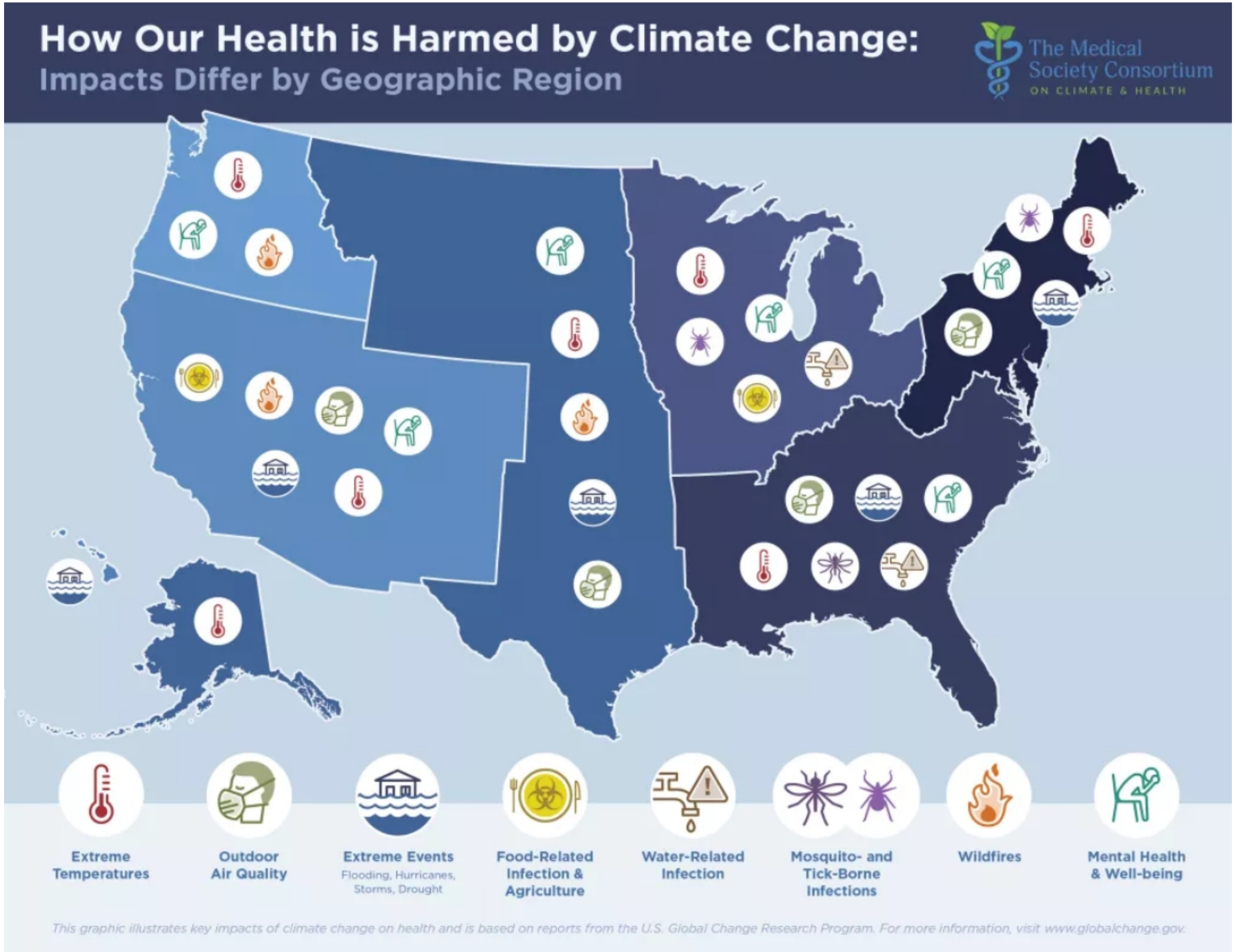
Jayati Chhabra (Thesis Advisor: Tarek Rakha, Ph.D.)
Master of Science Student| High Performance Building
School of Architecture | College of Design
Georgia Institute of Technology
jayatichhabra@gatech.edu

Contents

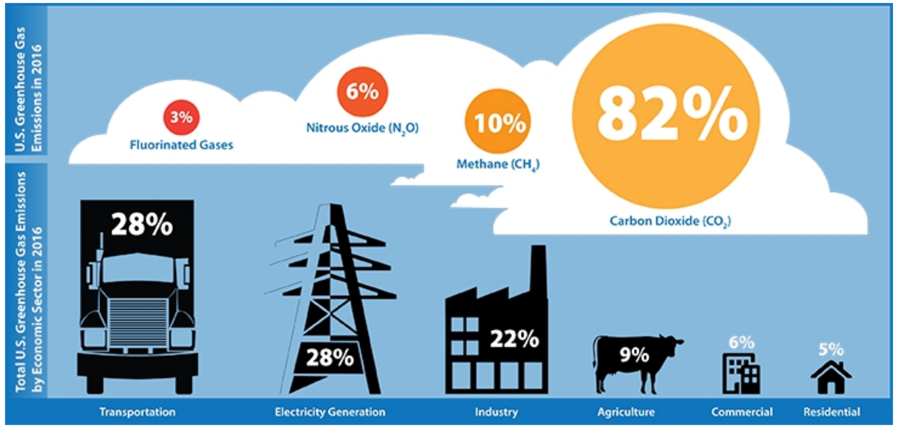
1 Introduction

Carbon Sequestration?

Carbon Capture and Storage



(Image: © The Medical Society Consortium on Climate & Health



CO2 is the most important long-lived "forcing" of climate change. Humans have increased atmospheric CO_2 concentration significantly which has led to extra heat being trapped near the surface of the Earth, causing temperatures to rise.

Carbon sinks

(Image: Youtube/ACCIONA)

According to Intergovernmental Panel on Climate Change (IPCC), it is required to **halt the temperature rise at 1.5C above pre-industrial levels** otherwise it would lead to worse heatwaves, drought and flooding, collapse of ice sheets in Greenland and Antarctica and much more.

ipcc

INTERGOVERNMENTAL PANEL ON
climate change

WMO UNEP

To stabilize temperatures, emissions need to reach net zero and stay there. That means cutting emissions as much as possible and drawing carbon dioxide out of the air to balance out any remaining emissions. Thus, it is impossible to achieve this without **Carbon Capture and Storage/Direct Air Capture (DAC) techniques**. With structures being spread widely, carbon sequestration techniques integrated in buildings can prove to be a great solution.

Creating a taxonomy of CS techniques that can be integrated in the built environment and consolidate the influencing design factors to enable the prediction of biotic techniques' CS potential at the schematic design stage.

Objectives

Recognizing Carbon Sequestration techniques in the built-environment

Evaluating and analyzing their integration potential in architectural practice.

Modeling framework to estimate the amount of carbon that can be sequestered by a structure (Biotic CS techniques)

Identifying literature and research gaps for development

Literature Review

Chapter 1
Introduction

Background
Research Overview

Chapter 2
Literature review

Classification of CS Techniques
Quantitative Literature Review
A comparative study
Qualitative Literature Review

Tool Development

Chapter 3
Tool workflow – Biotic techniques

Overview
Development Process

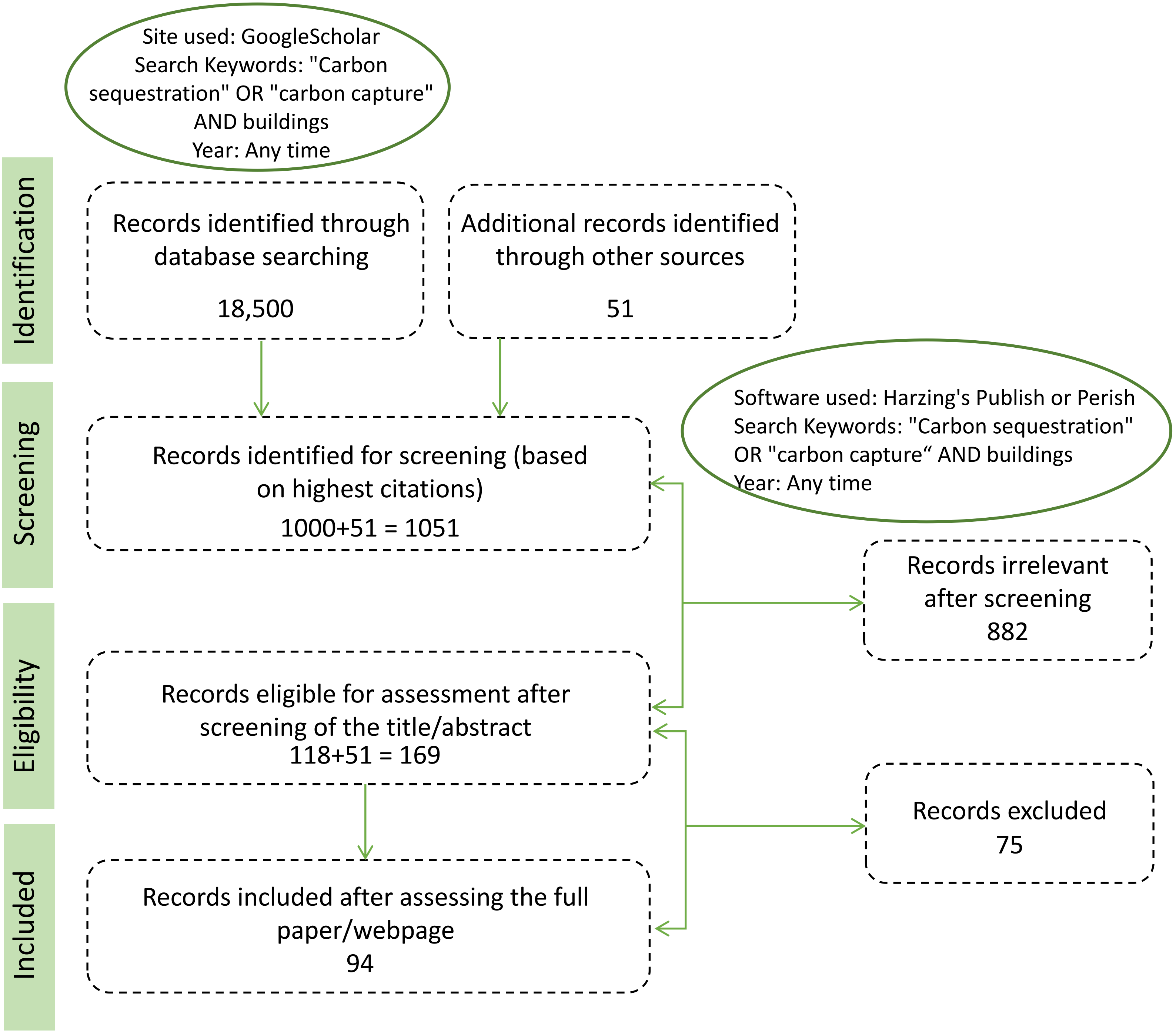
Chapter 4
Results, Conclusions, and Discussion

Scope and Limitations (Literature 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.
- Literature reviewed from English language domain only.
- Falls only under the year span of 2000 – August 2020 to prevent inclusion of any obsolete technique in the literature review.
- 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 research is limited solely to the carbon sequestration value and thus, respiration losses by the biotic techniques have not been taken into account.
- The scope and limitations for the tool workflow will be discussed later.

2 Literature Review

Literature review process for classification of Carbon Sequestration techniques



Carbon Sequestration Techniques

Biotic

Fig. 1

Green Roofs

Green roofs are vegetated roofs can sequester a lot of carbon content through photosynthesis.

Fig. 2

Vertical Green System (VGS) / Vertical gardens / living walls

Plants embedded in the vertical wall with a growing medium such as soil, water or substrate absorb carbon.

Fig. 3

Algae Curtains / Facades

Algae containing curtains use photosynthesis to store carbon while they release the oxygen back into the air.

Materials

Fig. 4

Carbon - negative building materials

Materials which are made out of sequestered carbon or waste like biomass which are formed by absorbing carbon.

Fig. 5

Carbon absorbing materials

Materials that sequester carbon after their application on the structure.

Equipment

Fig. 6

Smog free / Filter tower

High rise towers with a grid of air filters 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.

Fig. 1 2018. iberflora.feriavalencia.com. February 22. https://iberflora.feriavalencia.com/en/arquitectura-diseno-sostenibles/.

Fig. 2 2019. Urban Climate Roof | ZinCo Green Roof Systems. August 1. https://zinco-greenroof.com/systems/urban-climate-roof.

Fig.3. 2018. October 30. http://www.ecologicstudio.com/v2/project.php?idcat=3&idsubcat=71&idproj=174.

Fig. 4 2015. Elegantembellishments.tumblr.com. February 6. https://elegantembellishments.tumblr.com/post/110243857419/building-with-carbon-negative-materials.

Fig 5. Geoffroy deCrecy

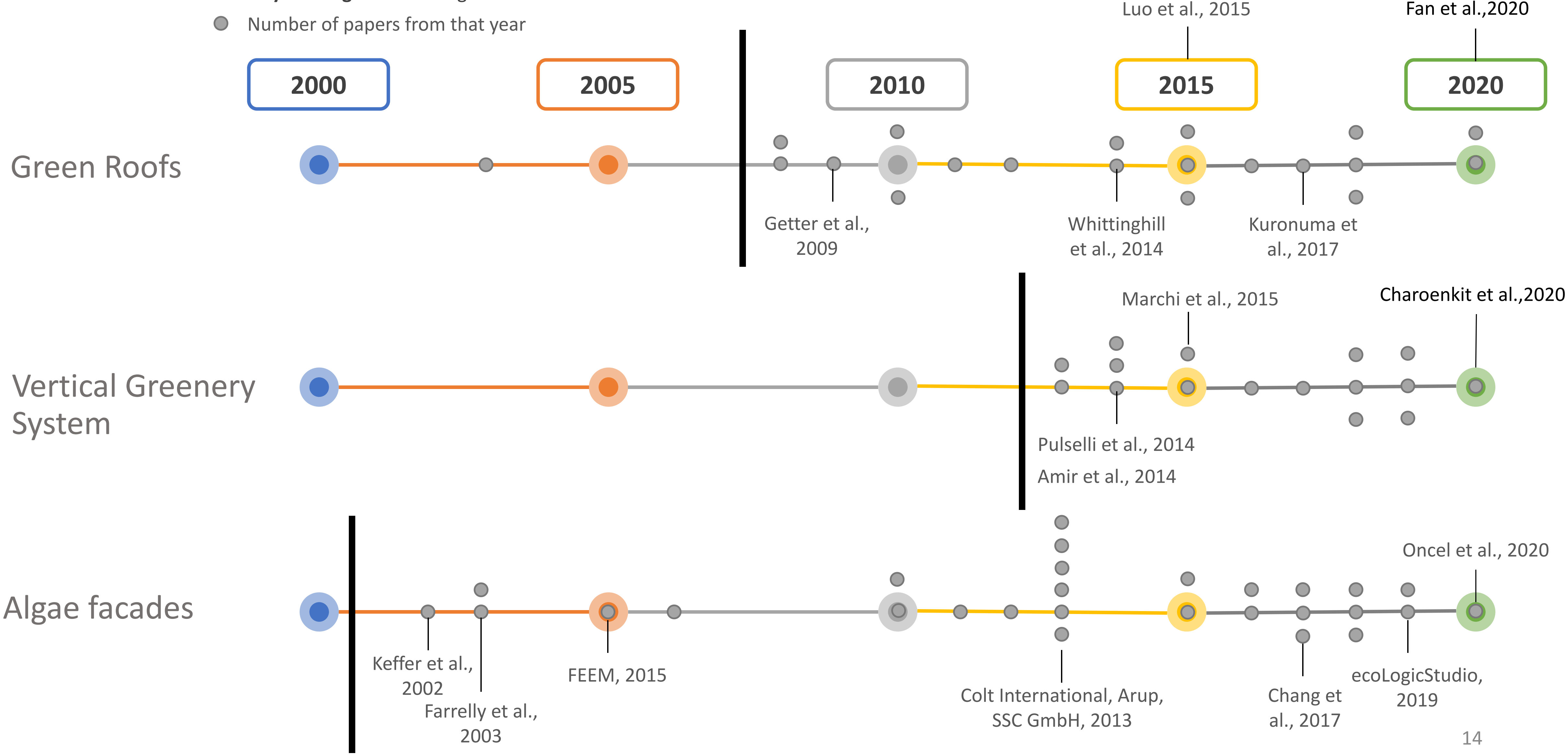
Fig. 6 Fessenden, Marissa. 2015. smithsonian.com . September 21. https://www.smithsonianmag.com/smart-news/tower-dutch-park-cleans-air-smog-180956687/.

Quantitative Literature Review

BIOTIC TECHNIQUES

Literature Review

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

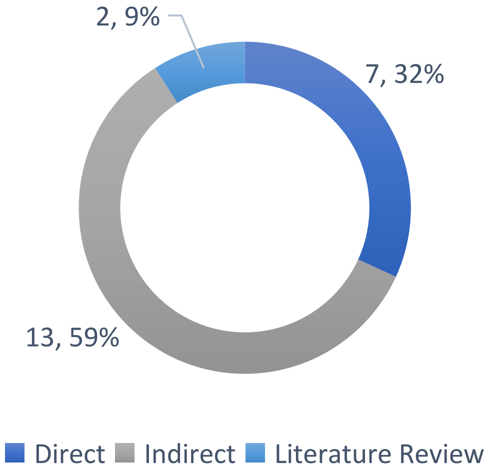


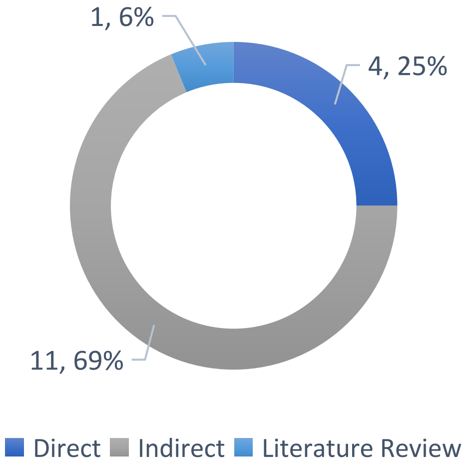
Green Roofs

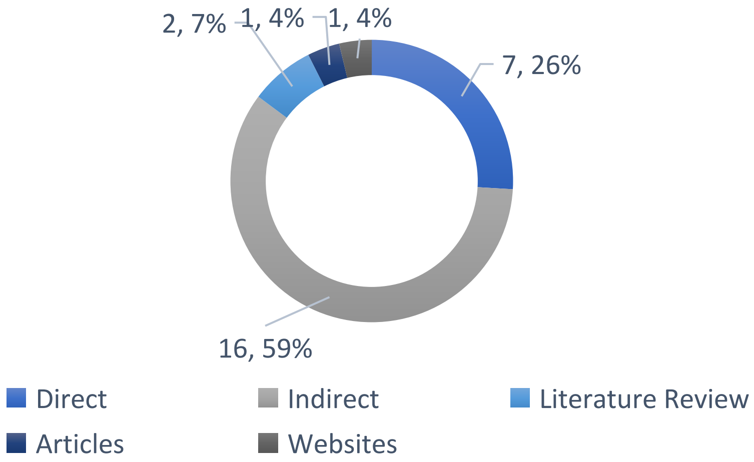
Vertical Greenery System

Algae facades

	Green Roofs	Vertical Greenery System	Algae facades
Search words:	Green roof carbon sequestration, Green roof CO2 sequestration	Vertical greenery system carbon sequestration, Living walls carbon sequestration	Microalgae carbon sequestration, Algae facades carbon sequestration, Algae CO2 sequestration,
Published papers:	22	16	28
Direct CS Potential:	7 (excluding 2 literature reviews)	4 (excluding 1 literature review)	7 (excluding 2 literature review and 1 website)







Direct: Papers that include measurement of the CS potential of algae facades and give out values as the first-hand information.
Literature Review: Papers who provide CS potential values accumulated from other resources. They are the secondary sources of information.
Indirect: Papers that mention the carbon sequestration potential of algae facades but nor do they measure it themselves, neither do they provide any quantitative analysis.
Websites: Official web pages of the manufacturers of the product.
Articles: Written on the products online.

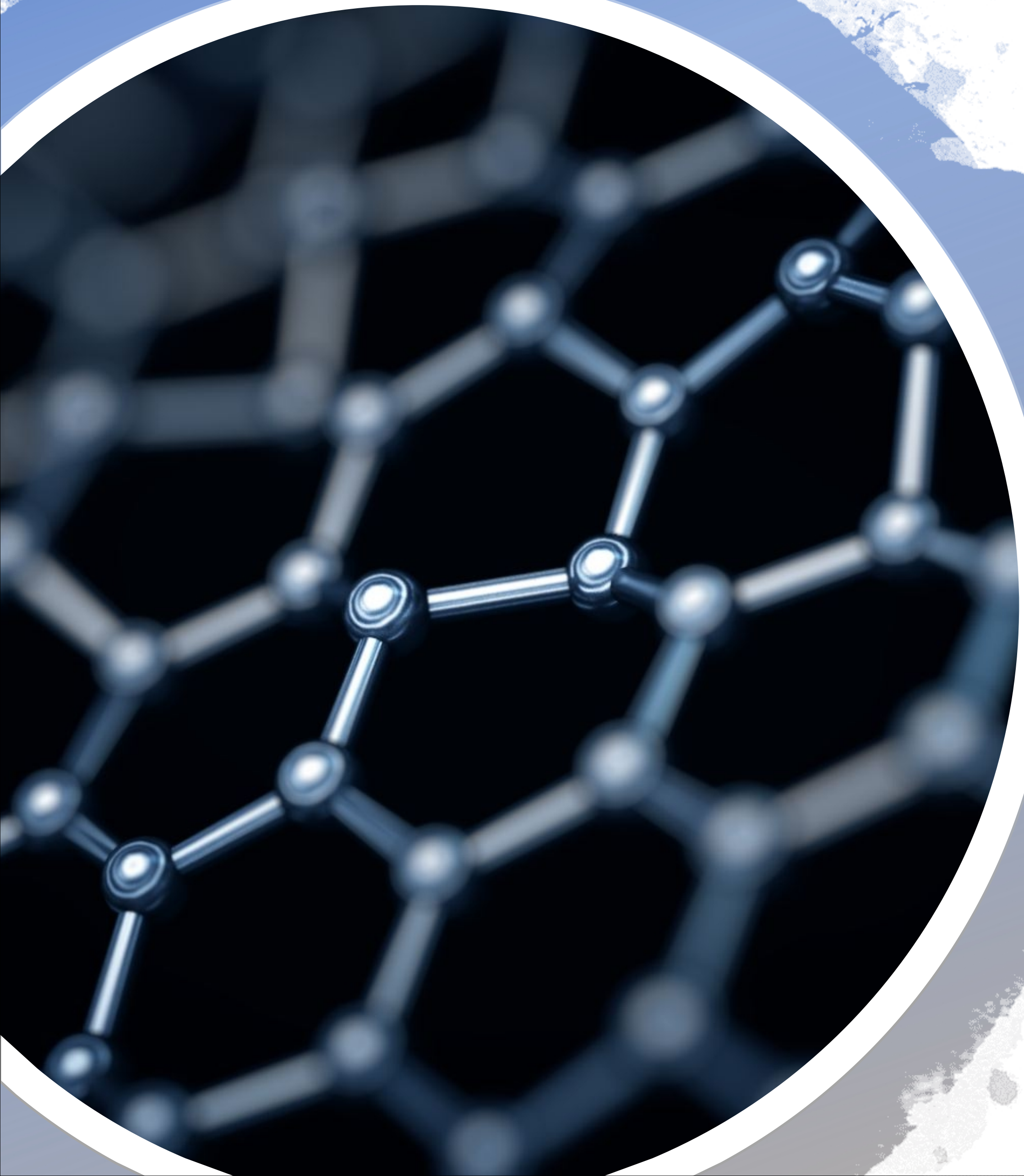
Green Roofs

Vertical Greenery System

Algae facades

	Green Roofs	Vertical Greenery System	Algae facades
References:	Getter et al., 2009 Kuronuma et al., 2017 Banta, 2018 Shafique et al., 2020 Fan et al.,2020	Pulselli et al., 2014 Amir et al., 2014 Marchi et al., 2015 Charoenkit et al.,2020	FEEM, 2015 Colt International, Arup, SSC GmbH, 2013 ecoLogicStudio, 2019
Annual carbon sequestration range (kg C/m. sq.)	**0.276 – 0.670 (Extensive)**	**0.037 – 0.270**	**2.430 – 2.970**
Average annual carbon sequestration (kg C/m. sq.)	**0.473**	**0.154**	**2.70**
A green roof of 100 m. sq. can sequester C equivalent to	**7.75 x** 	**2.5 x** 	**44 x** 

Average kg of carbon sequestered by 1 tree annually : 6.1



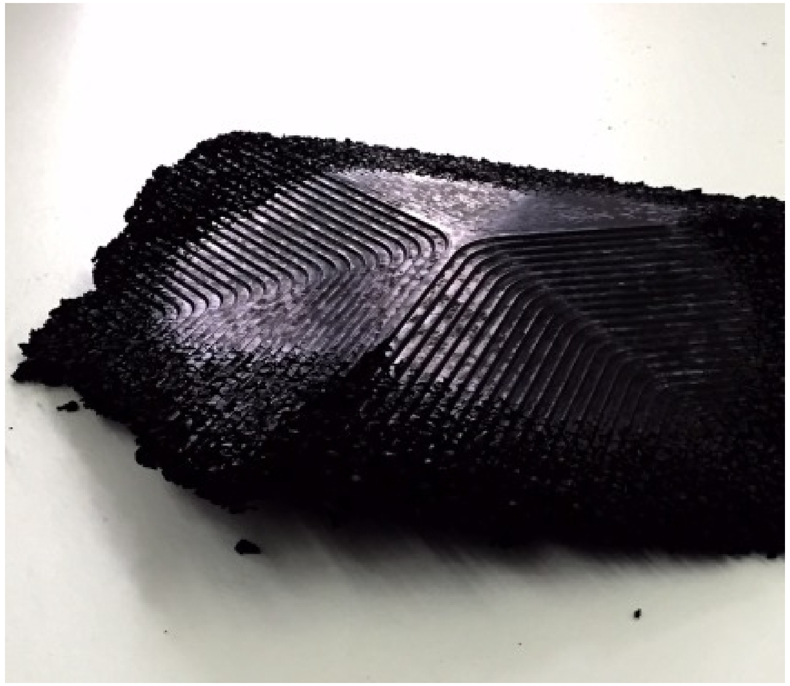
Qualitative Literature Review

MATERIAL & EQUIPMENT

Literature Review

Materials

Made of Air — SOLIDIA Cement — CO_2Concrete — CarbonCure — Carbicrete — Carbon8 Systems — Carbstone — Blue Planet



Case Study

Developer
Berlin-based studio Elegant Embellishments

About
Uses biomass, an organic waste, which absorbs and stores carbon dioxide. The baked carbon substance is mixed with a biodegradable binder to create a carbon-negative material that can be molded and shaped into various forms, including façade panels.

Carbon Sequestration Potential
34.02 kgC/ m. sq.

Demonstrated at:
'Charscraper' and first architectural installation of MOA facade panels at Munich Airport.

Literature Review

Equipment

Climeworks

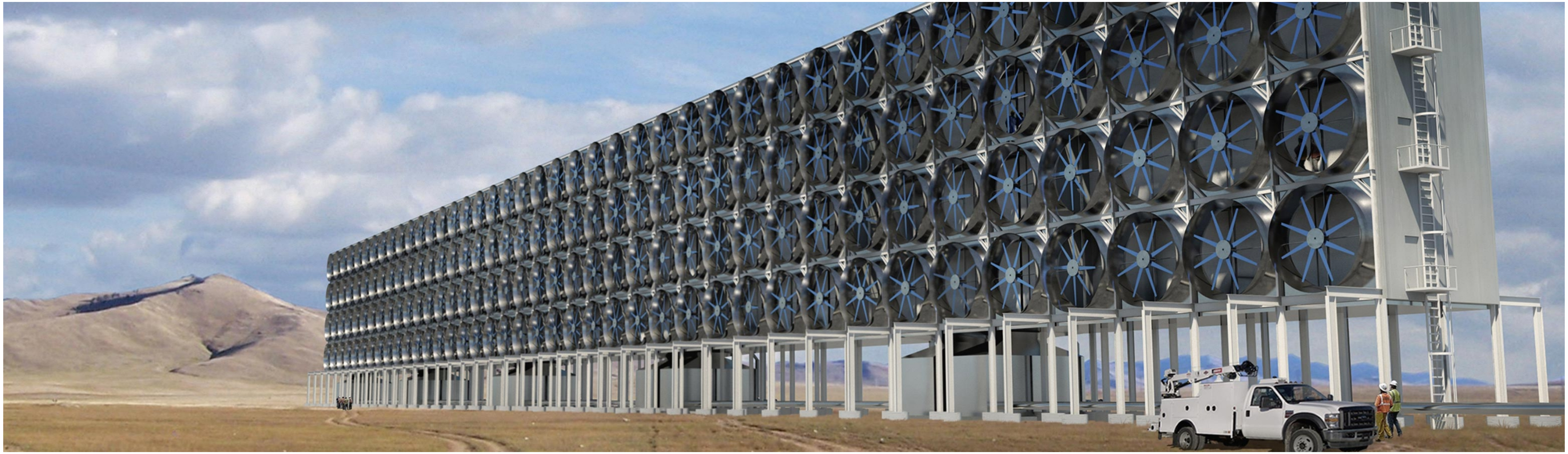
Carbon Engineering

Global Thermostat

Kilimanjaro Energy

Smog Free Tower

COAWAY



Case Study
Smog Free Tower

Developer
Daan Roosegarde

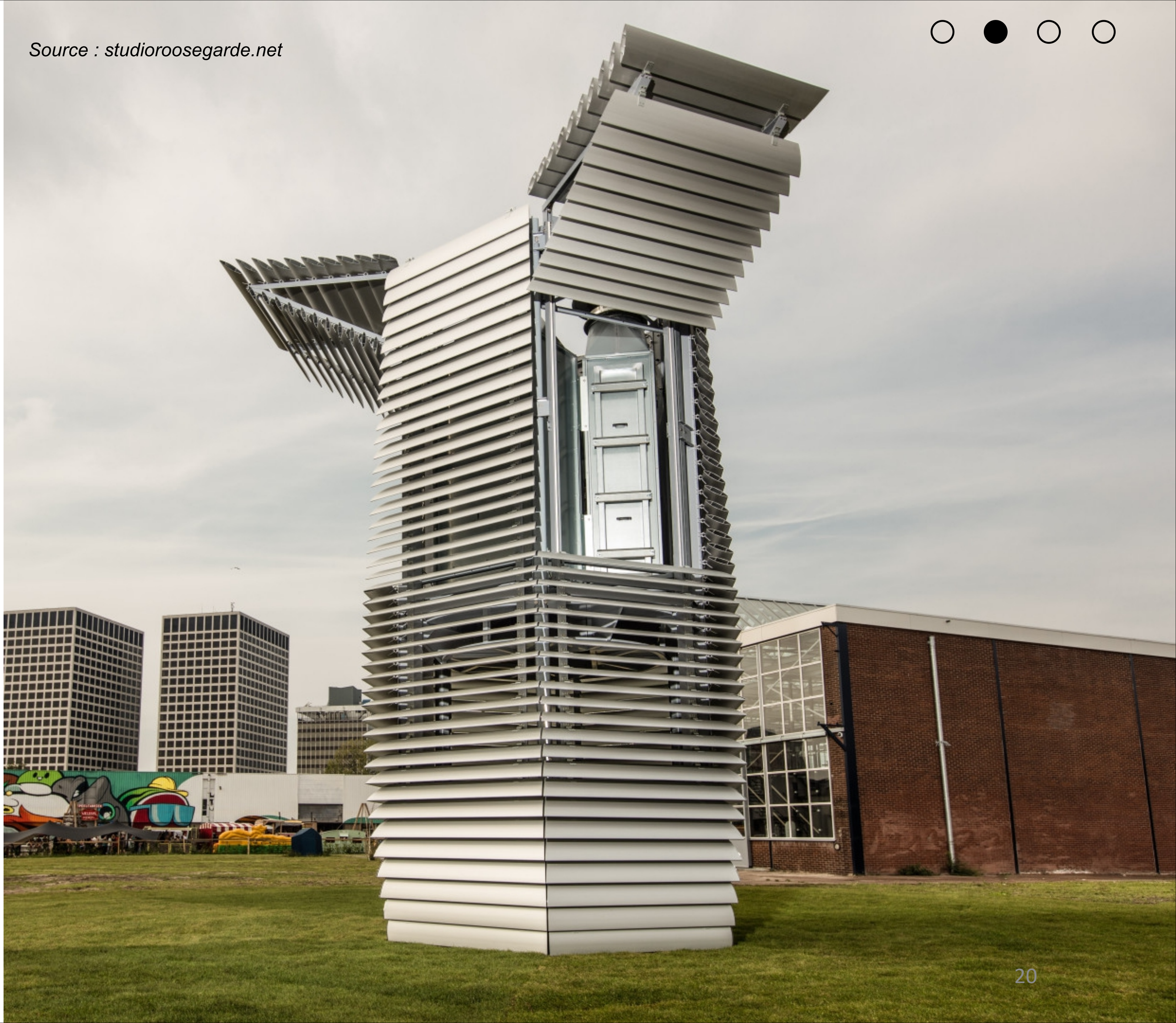
Size
23 feet tall = 7 m tall

Working Mechanism & Pre-requisites

TOWER CHARGING
Runs on 1400 watts of green energy
Aluminium
45 silver plates

Charging it with a small positive current, an electrode will send positive ions into the air. These ions will attach themselves to fine dust particles.
A negatively charged surface – the counter electrode – will then draw the positive ions in, together with the fine dust particles. Thus, the fine dust particles are collected together with the ions and stored inside the tower.

Cost
54000$



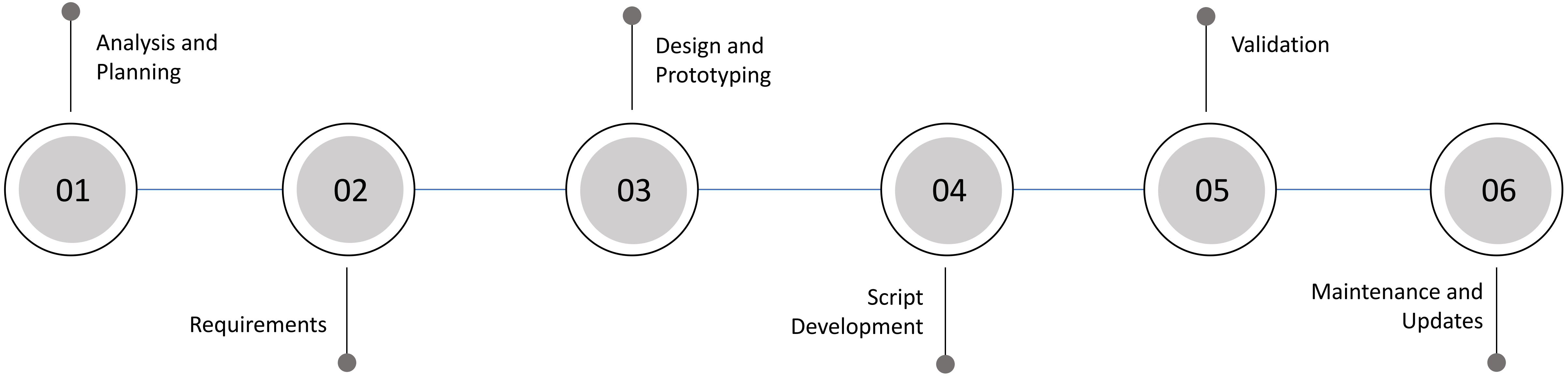
Source : studioroosegarde.net

3 Tool Workflow (Biotic Techniques)

Scope and Limitations (Tool 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 dioxide 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.

Development Process Flow



Development Process Flow

Aim: The reason why the tool is made.
Target user: Who will this tool be used by and for whom will it be beneficial.
Skillset: Preliminary training required to use the tool. Level of difficulty.
Planning type: The process chosen to develop this tool.

Analysis and Planning

01 — 02 — 03 — 04 — 05 — 06

Development Process Flow

01

02

03

04

05

06

Requirements

Study: Factors affecting the CS potential of the techniques

Climatic classification: Climate zones and regions targeted to analyse the working of the tool throughout the world

Software required: Spreadsheets and Rhino/grasshopper

Development Process Flow

Design steps: Steps that must be seen in the user interface.

Parameters and Variables: Inputs that are required such as location, geometry and Outputs that are expected such as CS potential are discussed.

Design and Prototyping

01 02 03 04 05 06

Development Process Flow

01

02

03

04

05

06

Script Development

Grasshopper Workflow: Components that are used to create the final workflow are shown.

Development Process Flow

Case Studies: Projects that provide the details about the façade, region, area, and associated CS potential are used for the validation of the tool.

Analysis: Error percentage determines how accurate the tool is.

Initial Validation

Development Process Flow

01

02

03

04

05

06

Maintenance and Updates

Updates required: The parameters that need to be updated with time are discussed.

Additions: Additional factors which can be incorporated in the same workflow to make the results more accurate are listed.

Development Process Flow

01 Analysis and Planning

Aim: The reason why the tool is made.
Target user: Who will this tool be used by and for whom will it be beneficial.
Skillset: Preliminary training required to use the tool. Level of difficulty.
Planning type: The process chosen to develop this tool.

02 Requirements

Study: Factors affecting the CS potential of the techniques

Climatic classification: Climate zones and regions targeted to analyse the working of the tool throughout the world

Software required: Spreadsheets and Rhino/grasshopper

03 Design and Prototyping

Design steps: Steps that must be seen in the user interface.

Parameters and Variables: Inputs that are required such as location, geometry and Outputs that are expected such as CS potential are discussed.

04 Script Development

Grasshopper Workflow: Components that are used to create the final workflow are shown.

05 Initial Validation

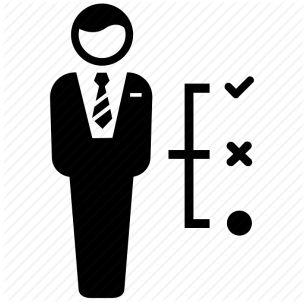
Case Studies: Projects that provide the details about the façade, region, area, and associated CS potential are used for the validation of the tool.

Analysis: Error percentage determines how accurate the tool is.

06 Maintenance and Updates

Updates required: The parameters that need to be updated with time are discussed.

Additions: Additional factors which can be incorporated in the same workflow to make the results more accurate are listed.



Aim

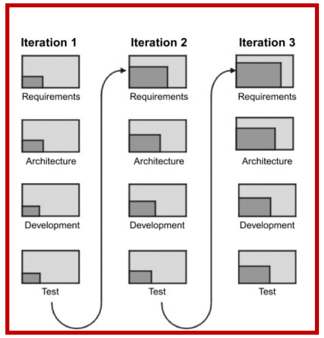
To enable architects to apply CS techniques and make decisions regarding their application in the early design stage.

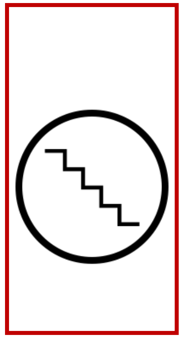
Target User

Architects
Designers
Consultants
Structural/Civil Engineer

Skillset required to use

Beginner level – Easy
Basic knowledge of Rhino and Grasshopper





Planning type

Incremental and Iterative Planning/Waterfall

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

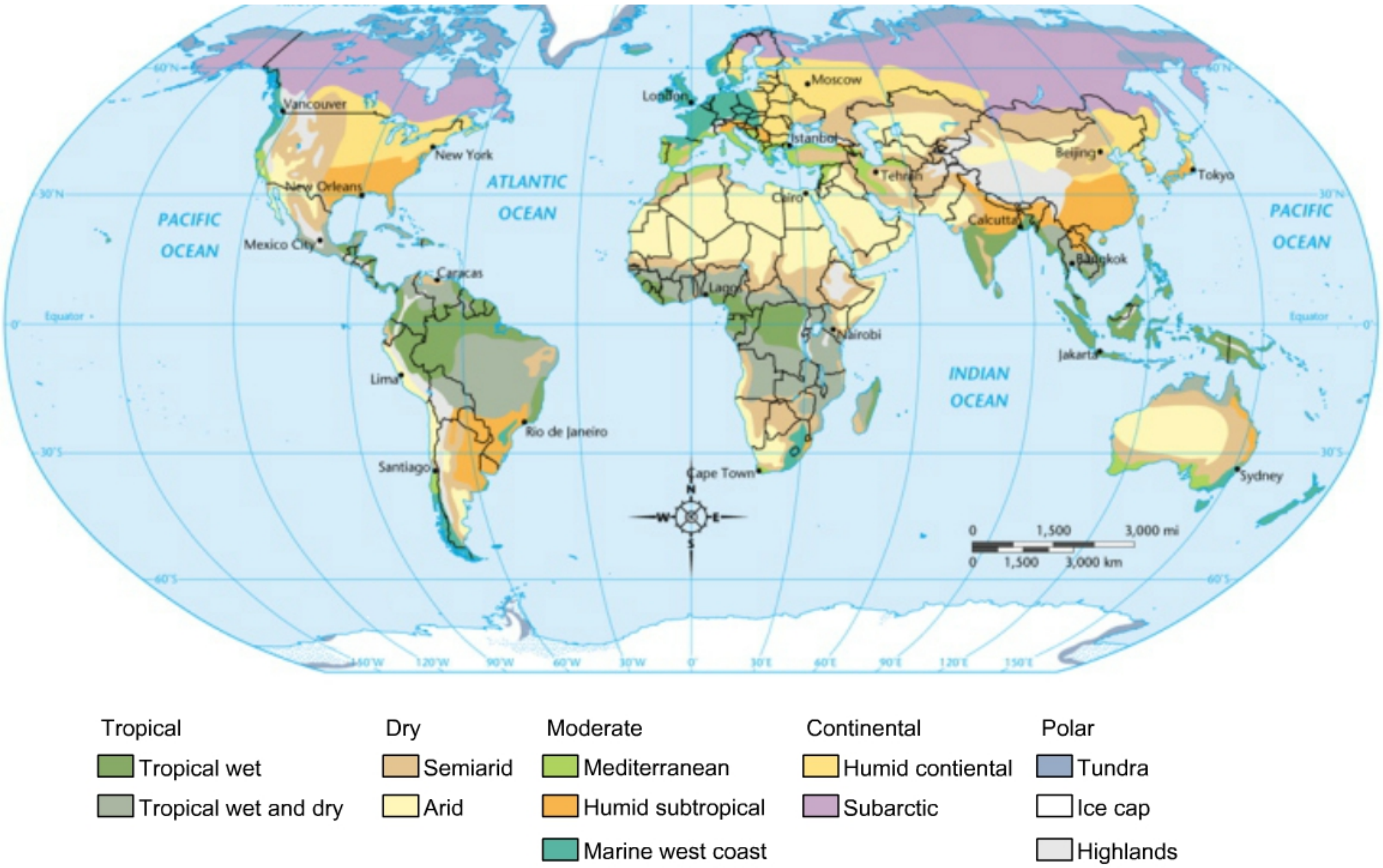
Requirements (Factors affecting the CS potential)

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 Kuronuma and Watanabe, 2016 Banta, 2018 Shafique et al., 2020 Charoenkit ◯⇗⇗ ∠Ⓛ, 2020	Species of plants (mechanism C3, C4, CAM)	**Sedum – CAM (Constant)**
		Temperature	Not explored
		Precipitation	Not considered since species is sedum (requires less/no water)
		Age (green roof)	Not considered yet
		Substrate depth (green roof)	**Extensive roofs - less than 15cm (Constant)**
		Illuminance/solar radiation	**Solar radiation – varied based on location**
		Substrate composition	**Natural soil (Constant)**
		Area/ No. of plants	**Area of the façade/roof (Varied based on geometry)**

02

Requirements (Factors affecting the CS potential)

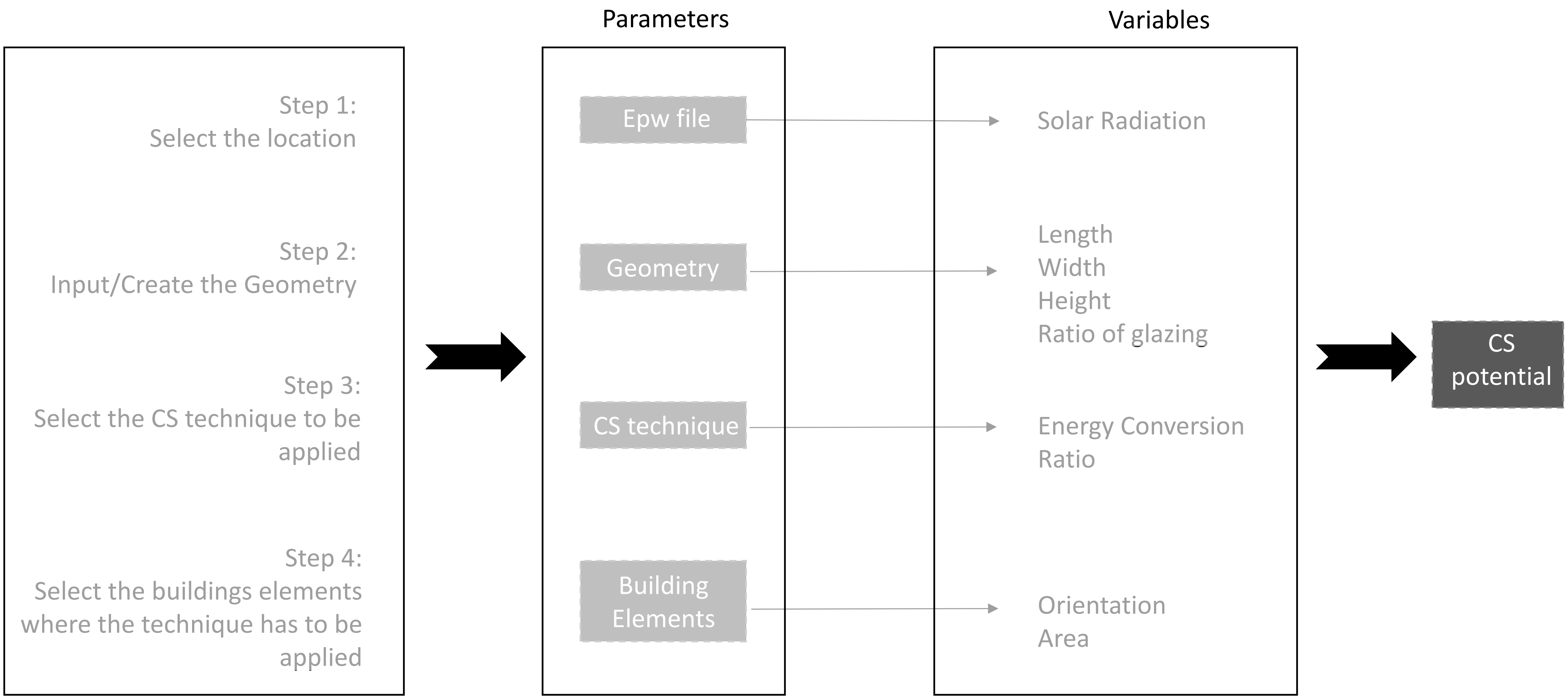
https://aamboceanservice.blob.core.windows.net/oceanservice-prod/education/pd/oceans_weather_climate/media/climate_zones.swf



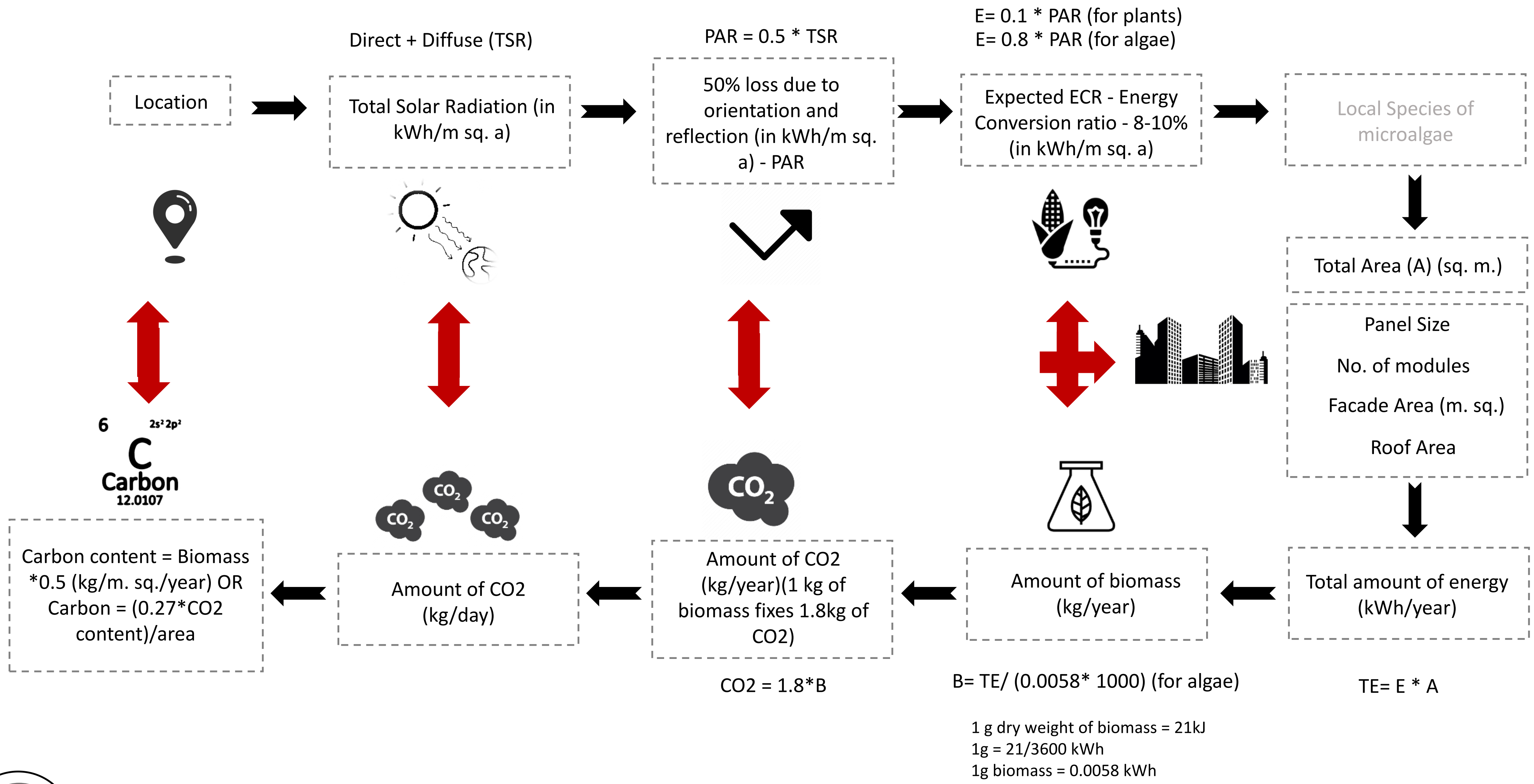
Tropical – Singapore
Dry – Australia
Moderate – Atlanta, Los Angeles, England/ New Zealand
Continental – Chicago, Canada
Polar – Antarctica, Greenland

02

Requirements (Classification of Climate Zones)

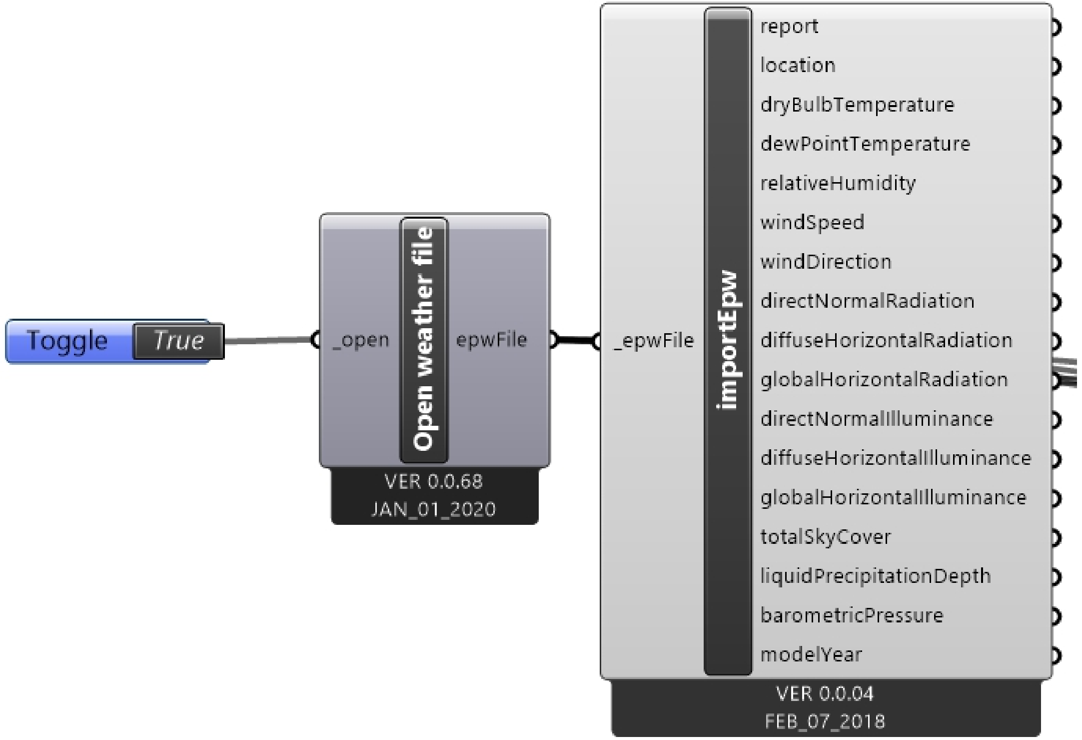


03 Design and Prototyping (User Interface)



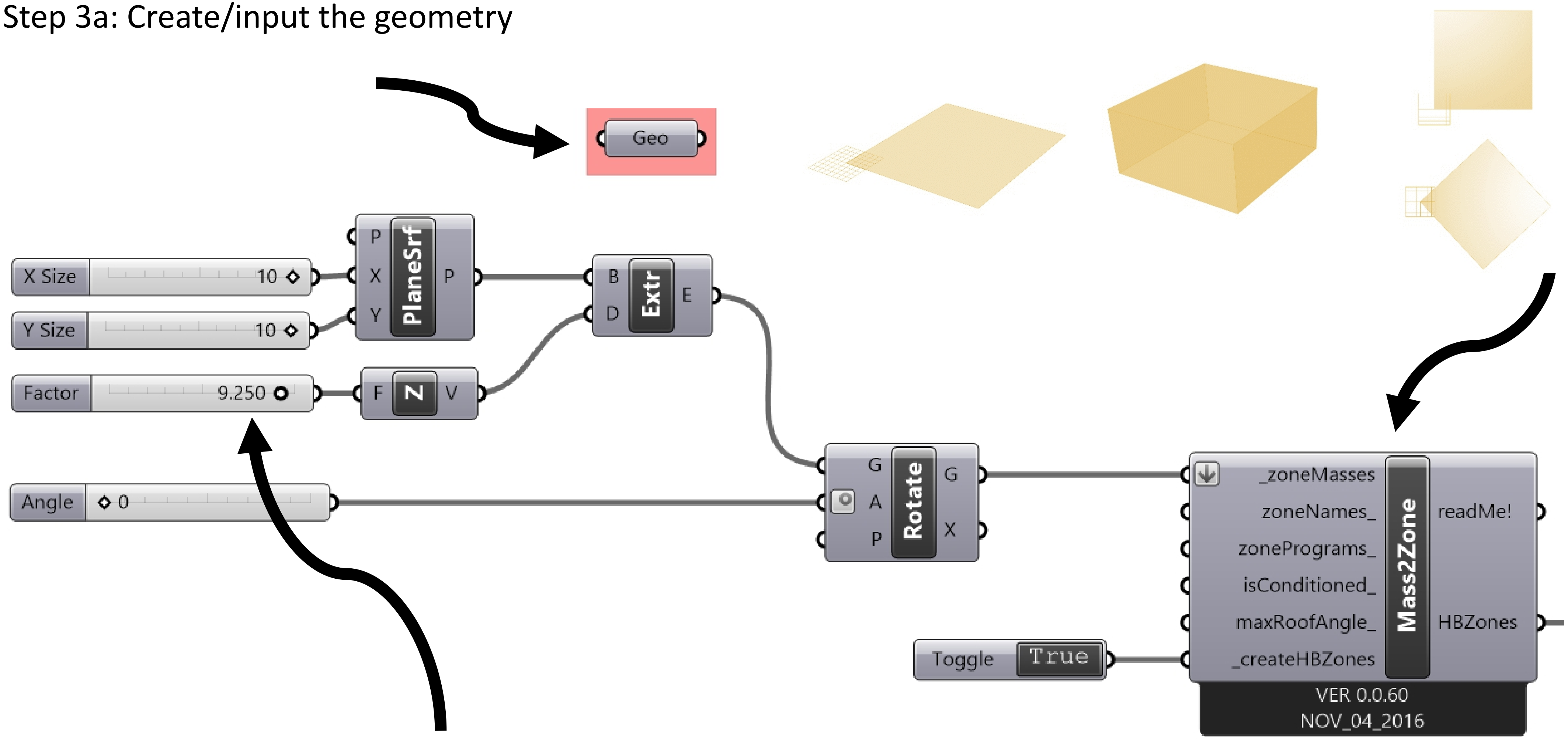
03 Design and Prototyping (Engine)

Step 1: Setting up the location

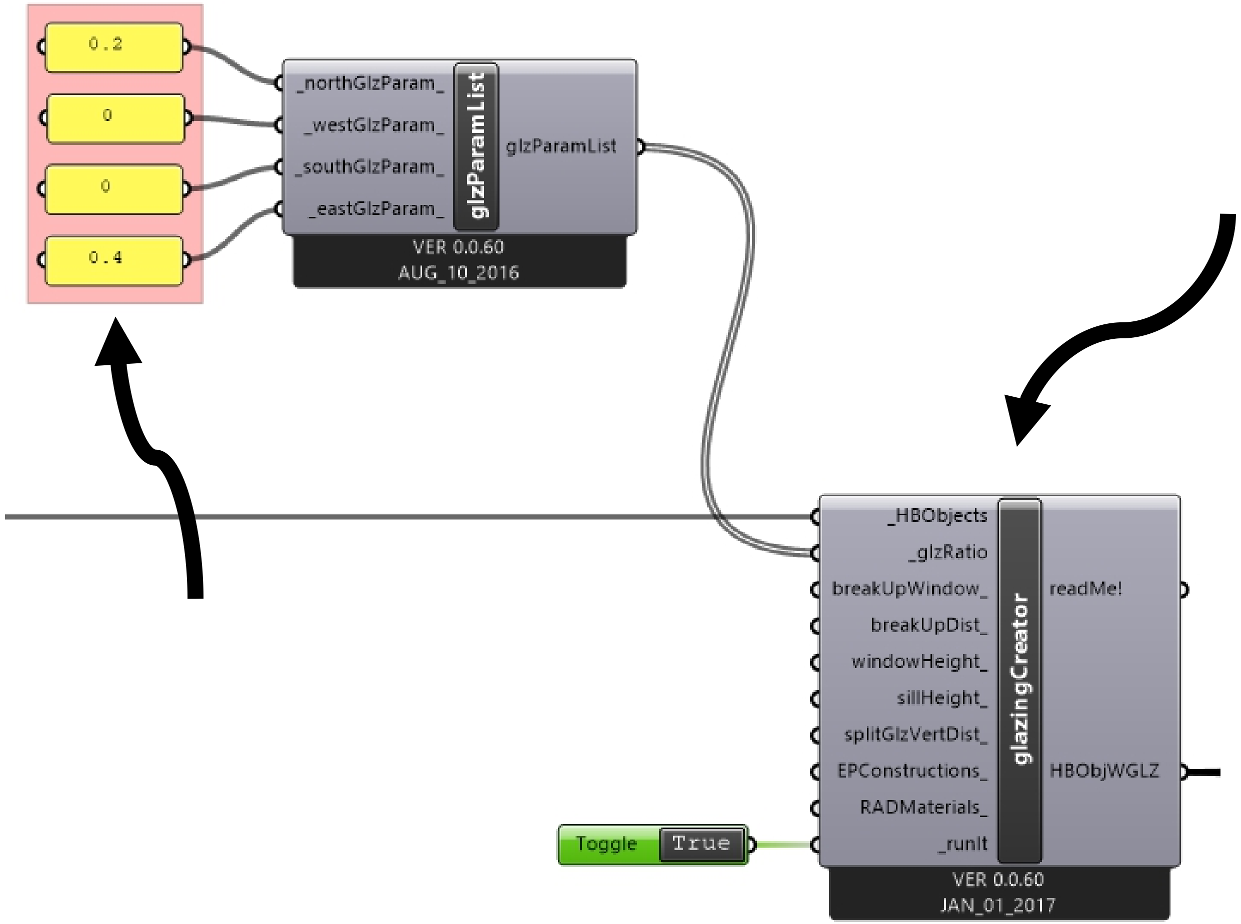


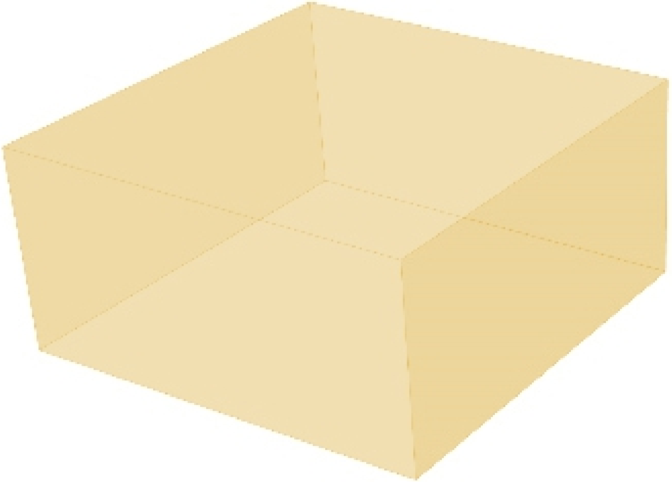
Step 2: Set the choices

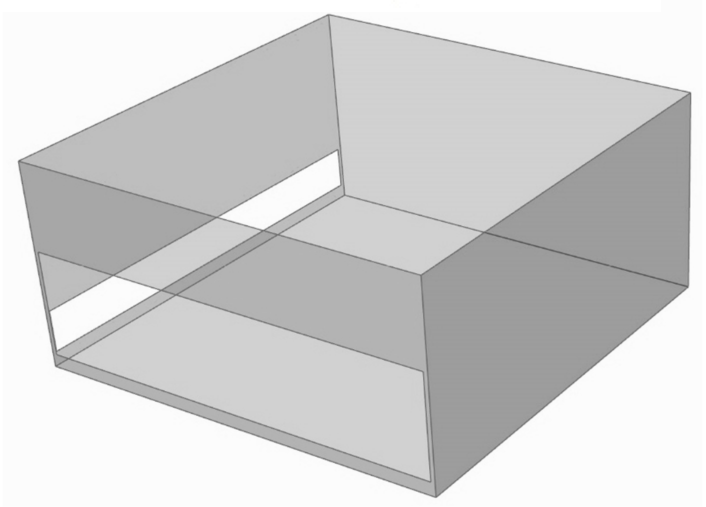
Step 3a: Create/input the geometry



Step 3b: Define the glazing ratios

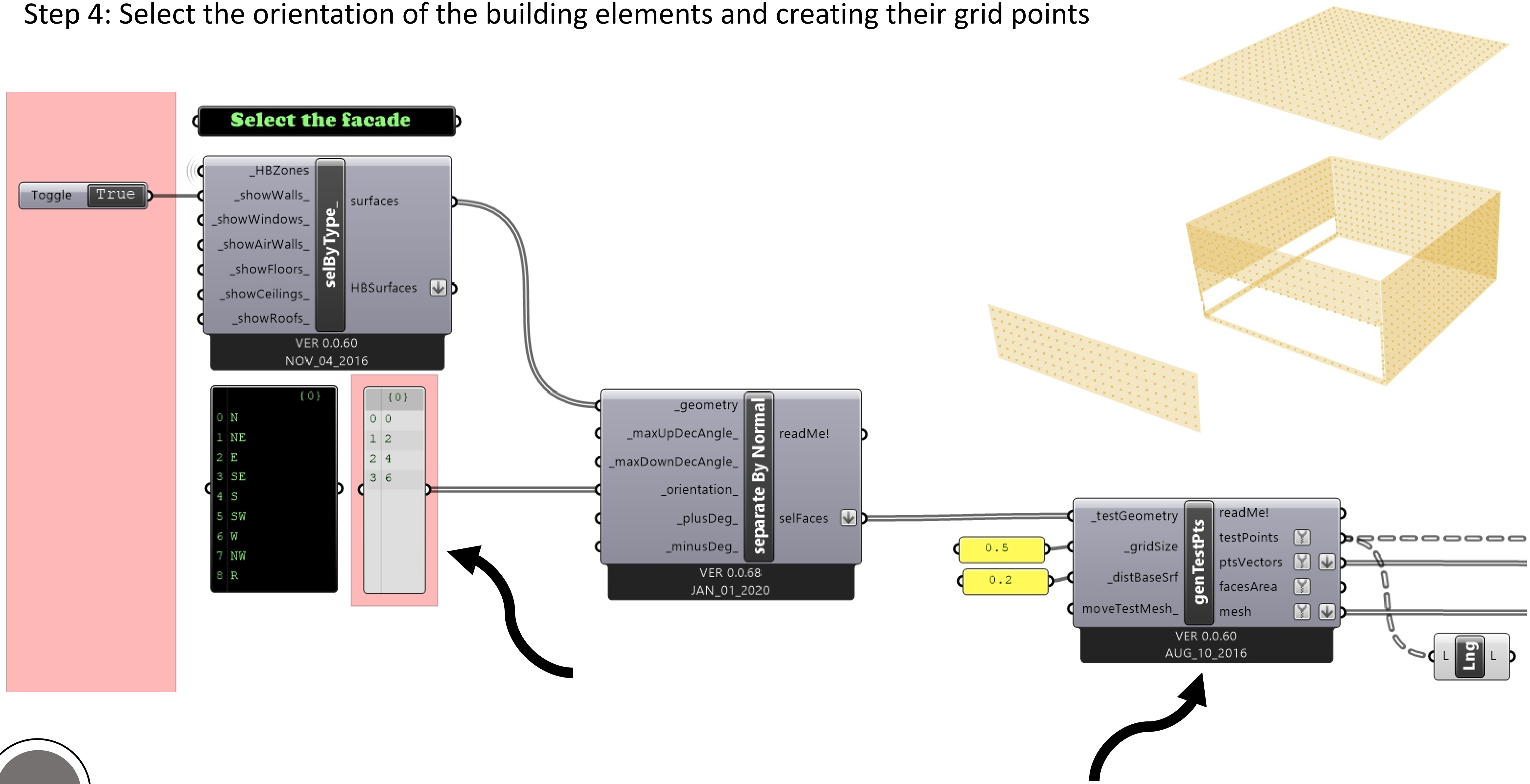






04 **Script Development**

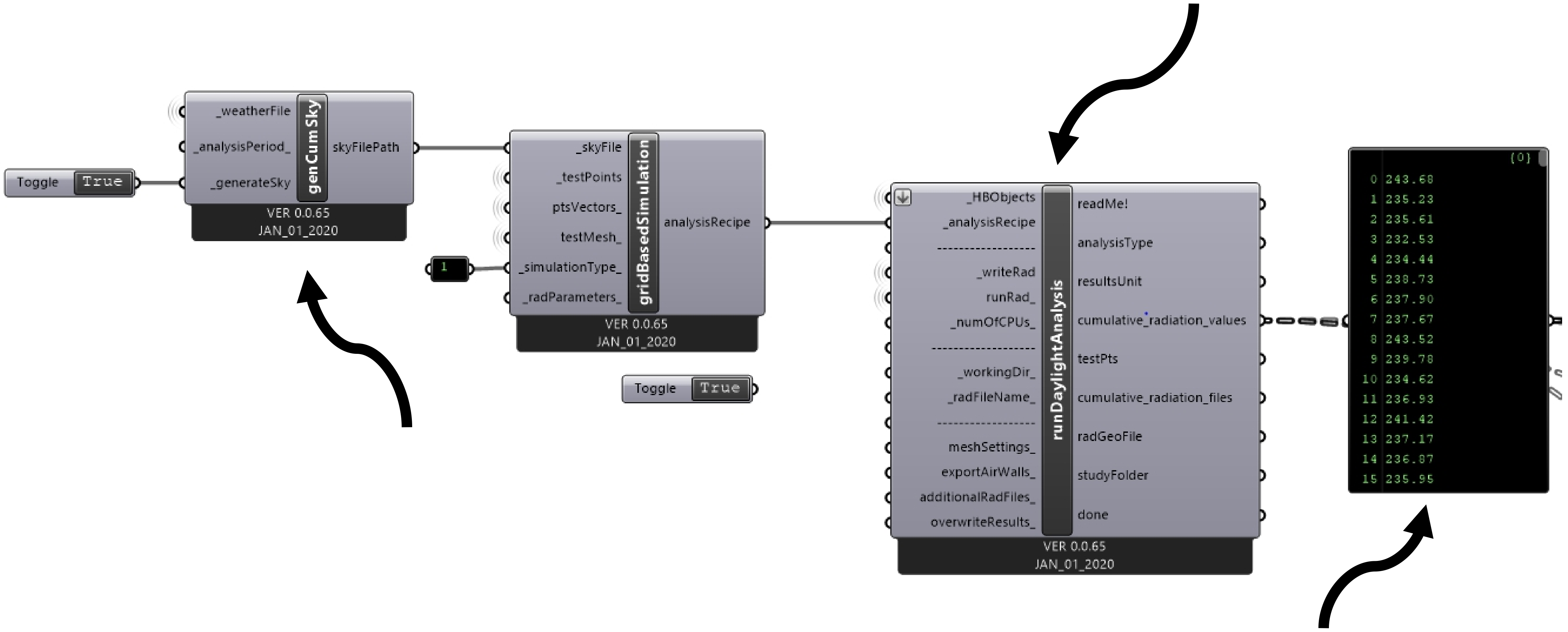
Step 4: Select the orientation of the building elements and creating their grid points



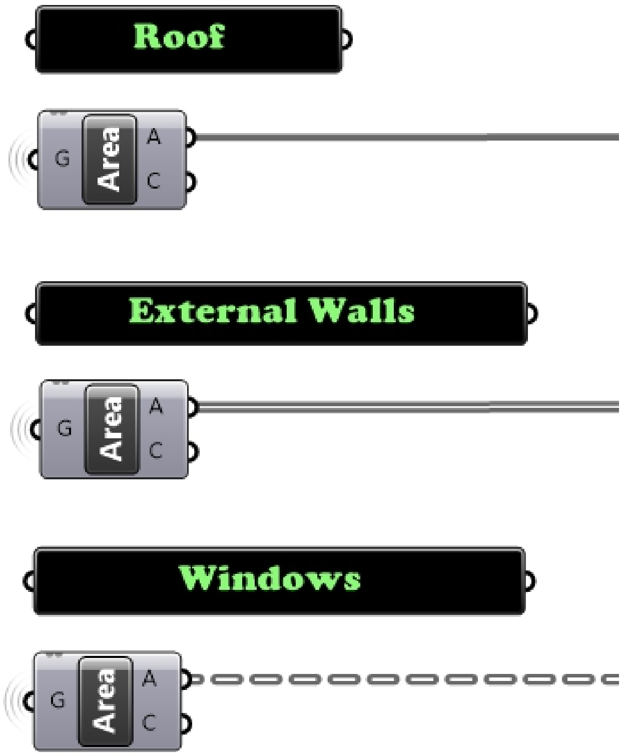
04

Script Development

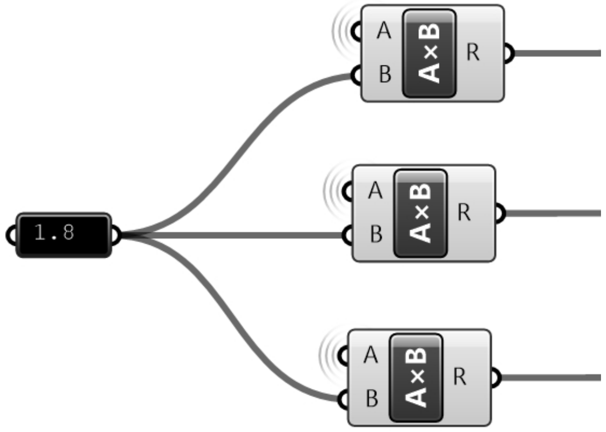
Step 5: Using analysis recipe, cumulative sky model and run daylight analysis to determine solar radiation



Step 5: Calculating the area of the selected building elements



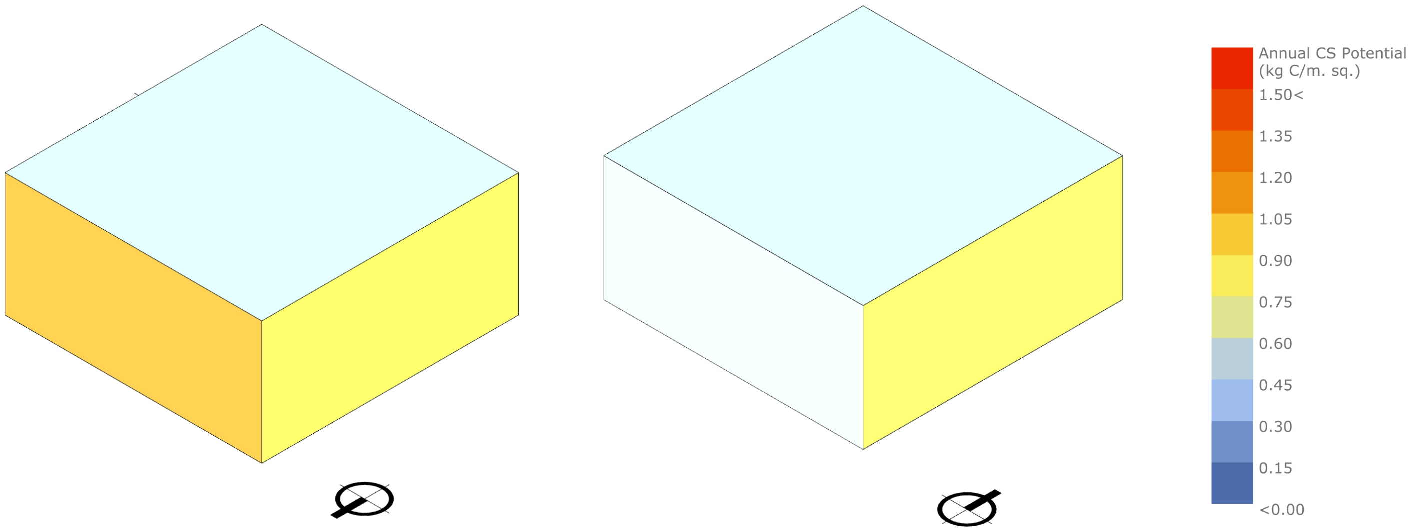
Step 6: Calculating the carbon dioxide sequestered/captured by the building elements



Roof

Façade /walls

Glazing



Getter et.al. 2009 (Green Roofs)

He 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.

3.73% error

ECR : 0.5%

	(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 CO_2/m. sq./annum)	0.375	0.389 (0.779 for ECR = 1%)

Kuronuma et.al. 2018 (Green Roofs)

He and his colleagues estimated the amount of carbon sequestered by three grass species and one sedum species since these are the most common plants for a Green Roof. Sedum species were tested in both irrigated and non-irrigated conditions, which has not been considered in the workflow.

	(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 CO_2/m. sq./annum)	Sedum →1.68 (Grass species → 2.5)	1.62 (2.69)

3.5% error

ECR : 0.6%

05 **Validation - Case studies identified (Green Roofs and VGS)**

Pulselli et.al. 2014 (VGS)

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.

	(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 (m²)	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%)

3.5% error

ECR : 0.5%

Amir et.al. 2014 (VGS)

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.

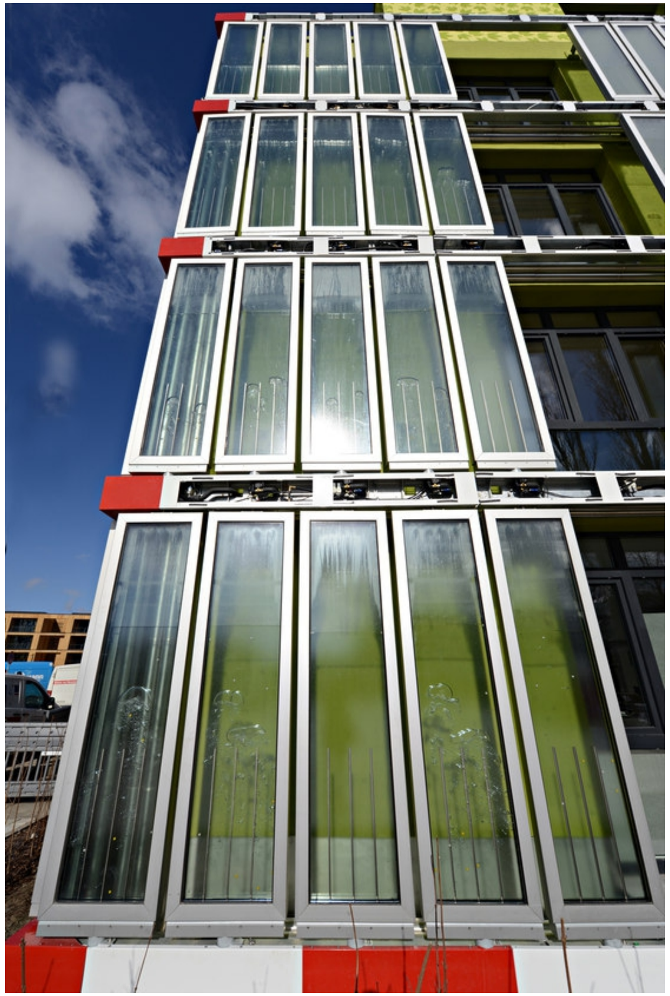
	(Amir et al. 2014)	Workflow
Location	Tropical climate (Malaysia)	Epw file of Penang, Malaysia (George Town)
Solar Radiation for the chosen building element (kWh)	-	653.4
Light energy equivalent of Photosynthetically Active Radiation (PAR)	-	326.7
Energy Conversion Rate (ECR)/Photosynthetic efficiency (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)

2.3% error

ECR : 0.7%

BIQ house

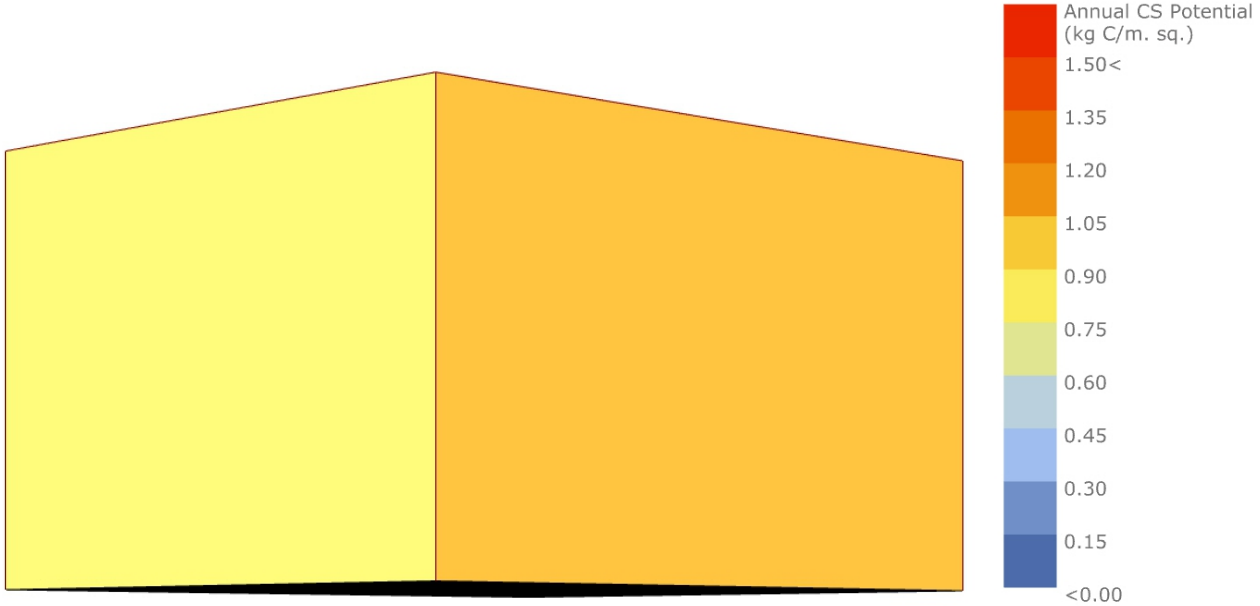
BIQ house in Hamburg, Germany is the world's first and the only live project featuring the bio-reactive algae façade panels. The flat plate algae photo bioreactors are called Solarleaf and each panel is 2.5m x 0.7m with a depth of 80mm.



05

Validation - Case studies identified (Microalgae)

BIQ house



05

Validation - Case studies identified (Microalgae)

BIQ house

There are 129 panels put up on the southeast and southwest façade of the house and are filled with fluid consisting nutrients to cultivate microalgae

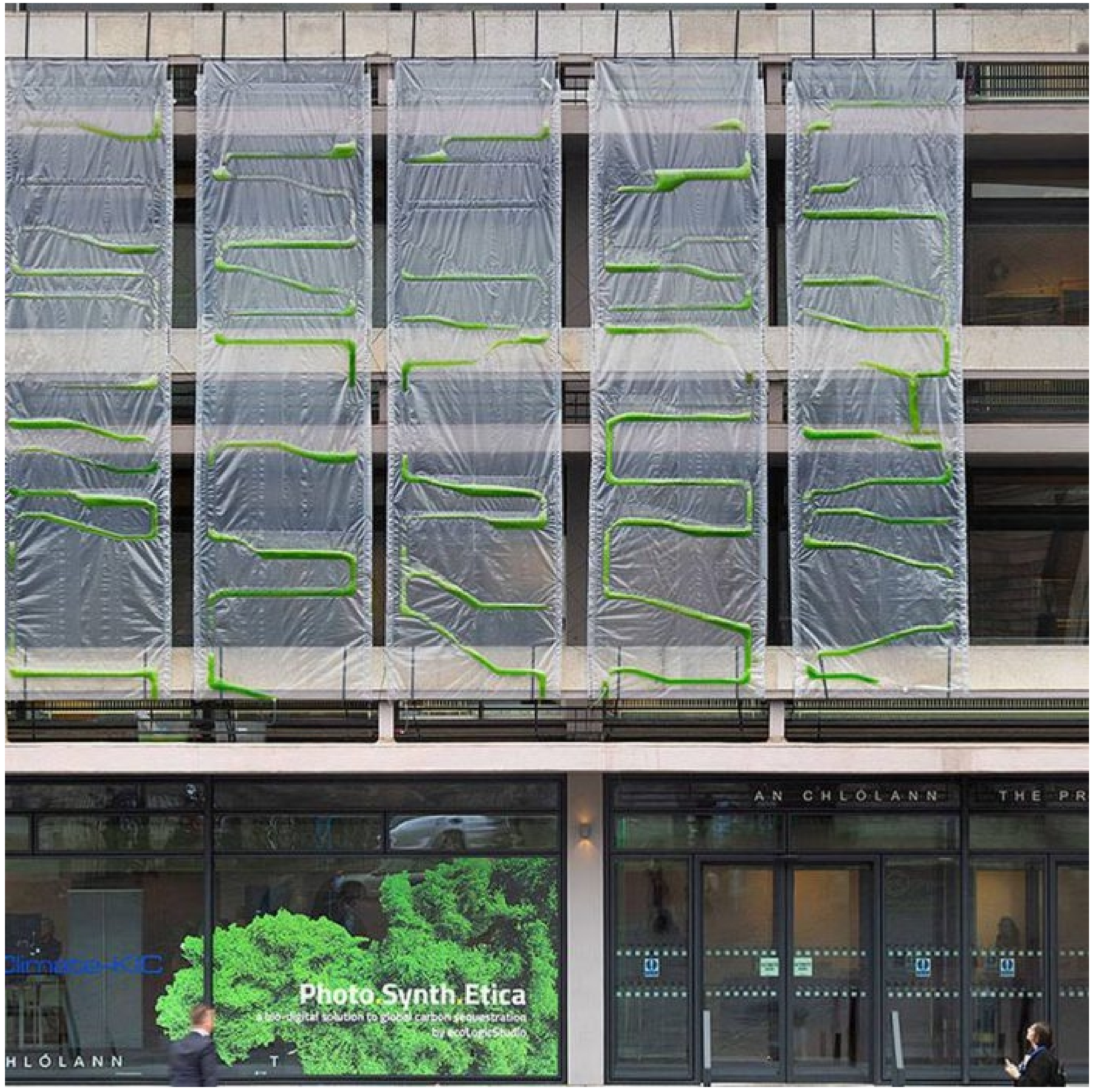
	BIQ House	Workflow
Size (m^2)	Plot size: 839 Gross floor area: 1600 (IBA_Hamburg 2013)	Area per floor: 340 approx. (Considering 4 floors and a 5th smaller one too) – 18.5 x 18.5
Location	Hamburg, Germany	EPW file of Hamburg, Germany
Solar Radiation	-	-
Light energy equivalent of Photosynthetically Active 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

4.4% error

ECR : 8%

Photosynthetica

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. Its first demonstration has been on the Printworks façade in the Climate Innovation Summit 2018.



05

Validation - Case studies identified (Microalgae)

Photosynthetica

Factors which might be responsible for a high percentage error.

- 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.

20% error

ECR : 8%

	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

05 **Validation - Case studies identified (Microalgae)**

Keffer and Kleinheinz 2002

An experiment was conducted in the lab using two fluorescent lamps 15m apart to estimate the CO_2 bio fixation.

	(Keffer and Kleinheinz 2002)	Workflow
Location	Lab: Cool white, fluorescent lighting (Average sunlight equivalent – 2.4 x 10^{19} – 3.0 x 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)

7.4% error

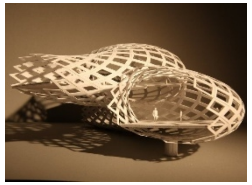
ECR : 4%

Addition of CS techniques

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.

Geometry

Freeform geometry governed by coordinates can be included in the workflow. Moreover, many more building elements like overhangs can be incorporated.



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.

PE/ECR

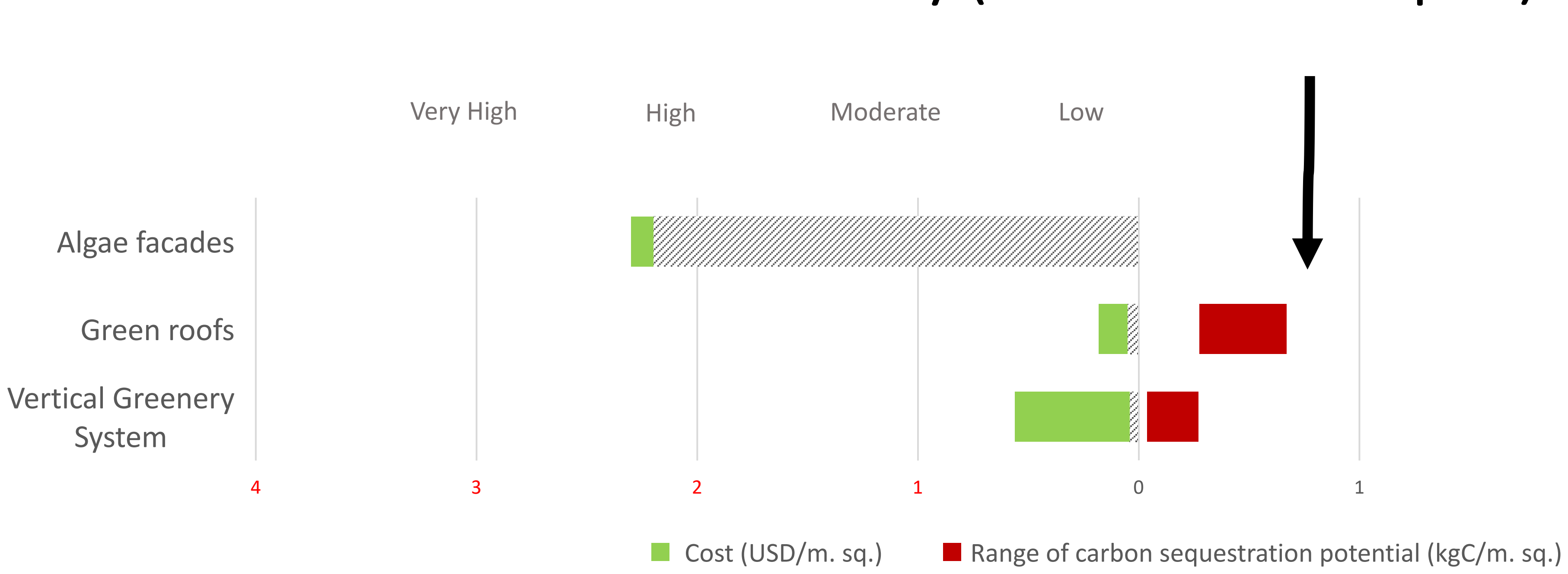
The PE/ECR value must be updated with advanced real-time project results to acquire more accurate Carbon Sequestration values.

Cost

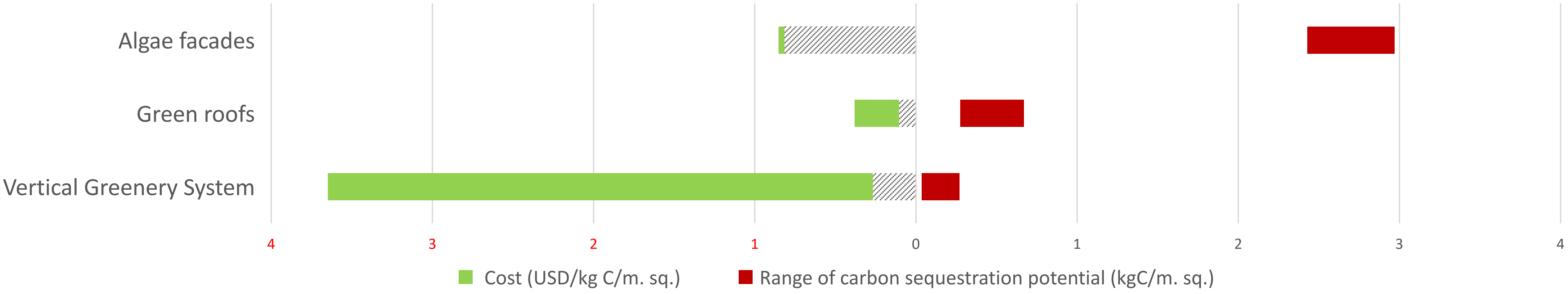
Financial aspects are often difficult to be included in a workflow since it fluctuates with regions as well as time. However, if the costs of all the techniques are normalized, they should be incorporated in the later stages of the workflow.

4 Results, Discussion and Conclusions

Inferences from the literature study (Biotic CS Techniques)



Without normalization



Updated Tool Workflow

Green Roof/VGS

Getter et.al. 2009	Kuronuma et.al. 2018	Pulselli et.al. 2014	Amir et.al. 2014
3.73% error ECR : 0.5%	3.5% error ECR : 0.6%	3.5% error ECR : 0.5%	2.3% error ECR : 0.7%

ECR : 0.5%

Updated Tool Workflow

Algae facades / curtains

Photosynthetica

20% error
ECR : 8%

BIQ house

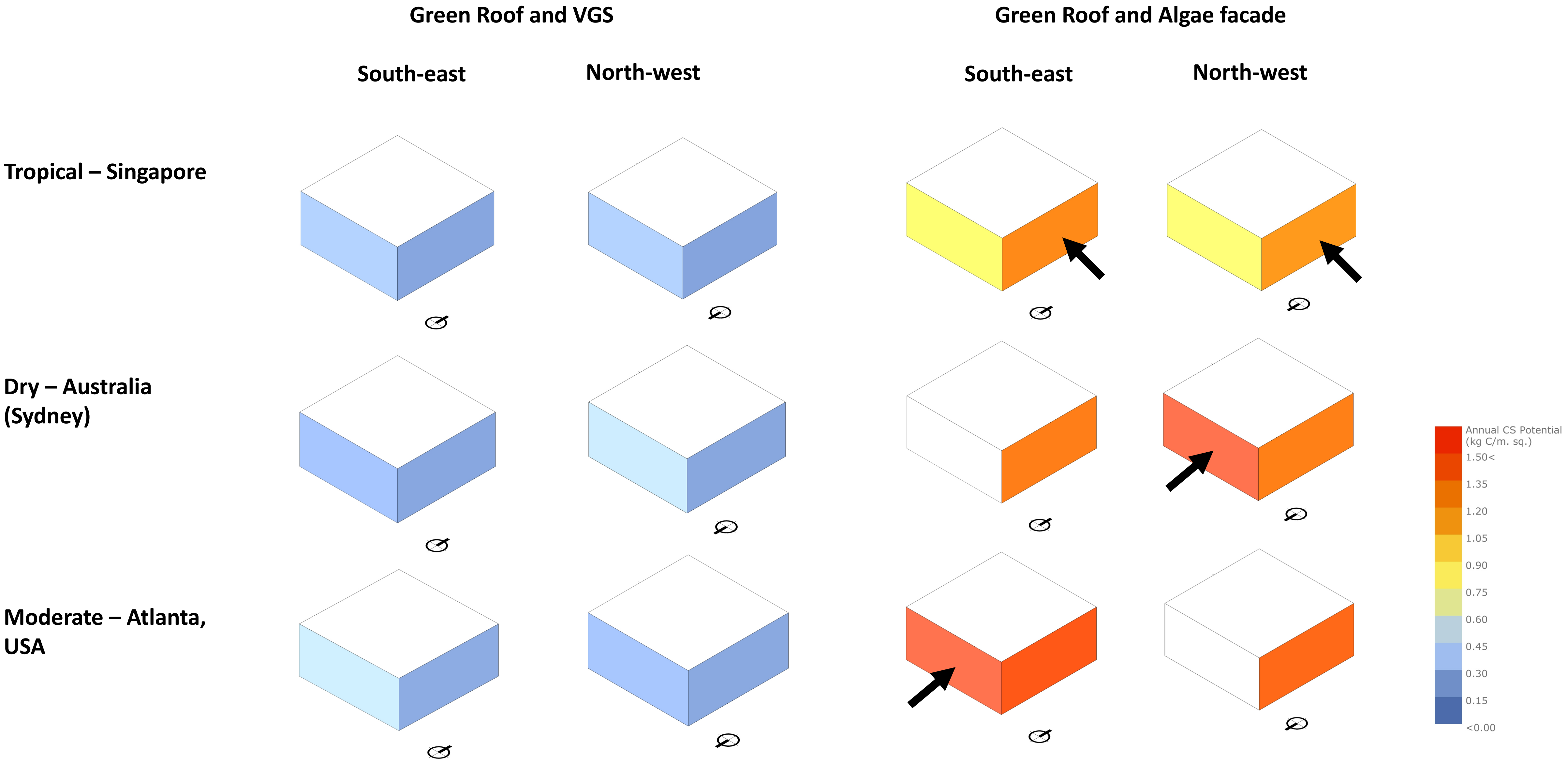
4.4% error
ECR : 8% (estimated)
ECR: 4.4% (Monitored results)

Keffer and Kleinheinz 2002

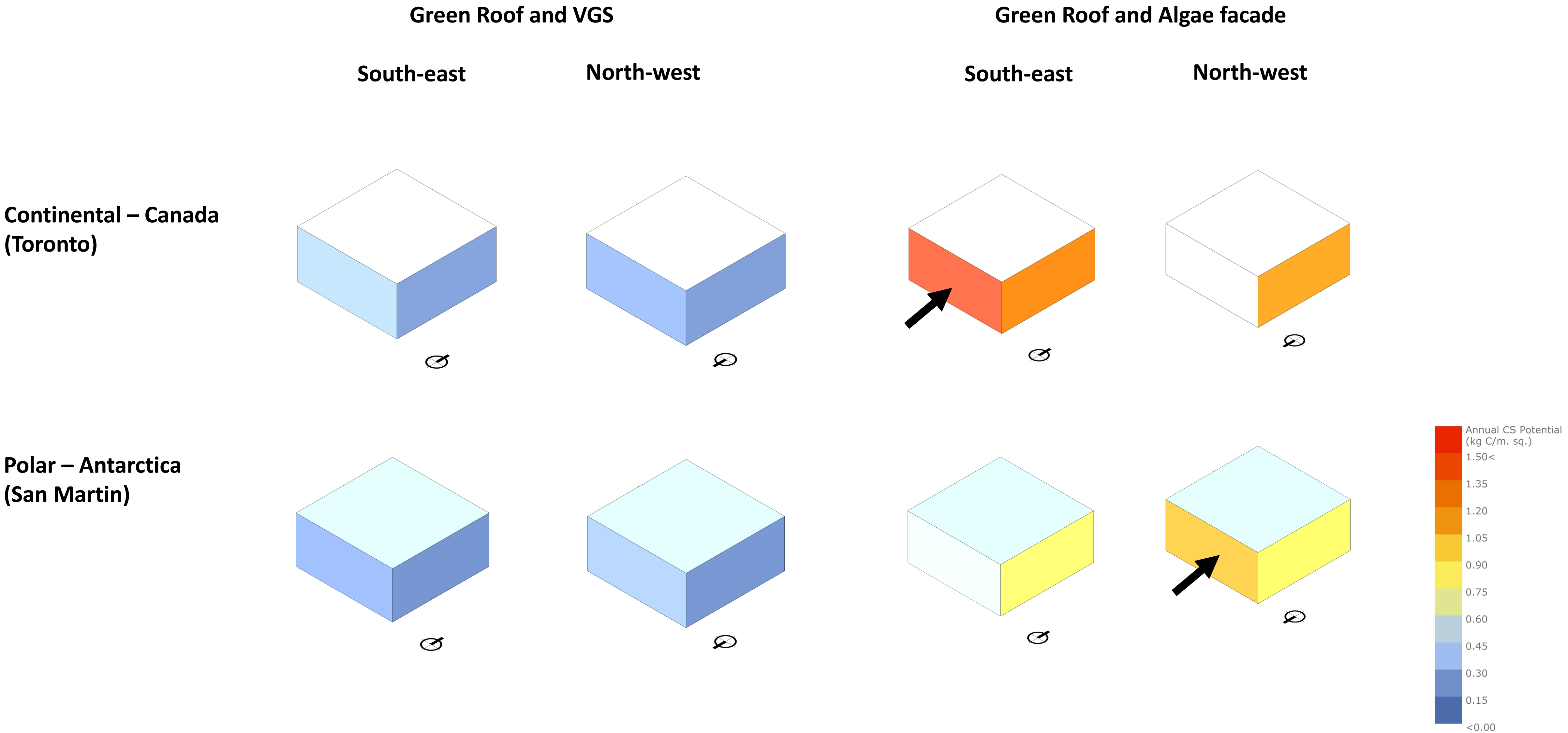
7.4% error
ECR : 4%

ECR : 4%

CS potential values for different climatic zones

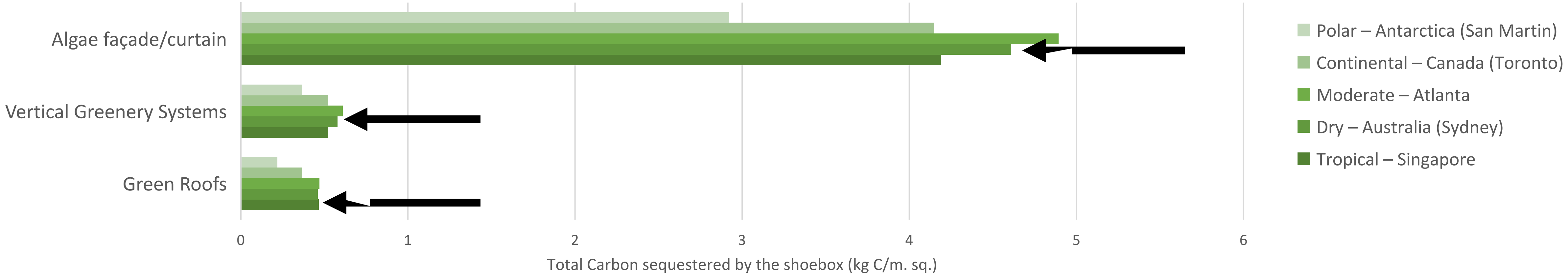


CS potential values for different climatic zones



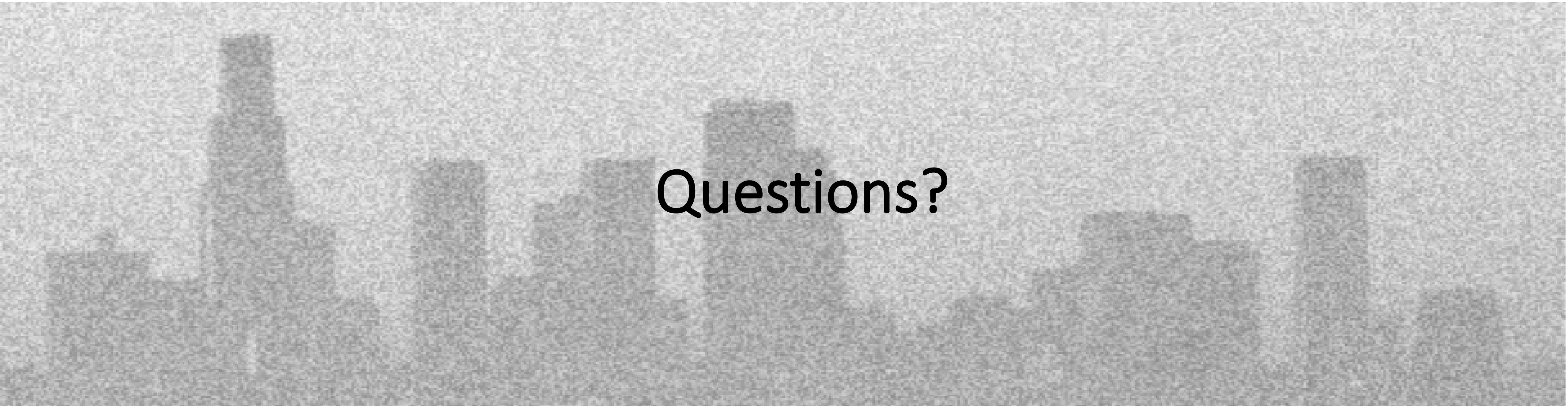
CS potential values for different climatic zones

	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



Conclusion

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



Building-integrated Biotic Carbon Sequestration Techniques : Overview and Simulation Workflow

Georgia Tech
High Performance Building Lab
College of Design

Jayati Chhabra (and Tarek Rakha, Ph.D.)
Master of Science Student| High Performance Building
School of Architecture | College of Design
Georgia Institute of Technology
jayatichhabra@gatech.edu