INTEGRATING CARBON CAPTURE INTO BUILT-ENVIRONMENTS

Evaluating the Viability and Integration Strategies of Direct Air Capture in Architectural Methodologies, Utilizing KOH Hollow Fiber Contactor Reactor

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ABSTRACT

This paper aims to present and assess the prospective environmental feasibility and efficacy associated with the integration of Direct Air Capture (DAC) technology into diverse design methodologies within contemporary architecture. The primary focus of adjusting the flow of the chemical process through various design parameters will be elucidated for the hypothetical application into buildings. This chemical process involves the scientific method of utilizing the hollow-tube fibers with potassium hydroxide (KOH) as the primary carbon absorbent, where the CO_2 contained ambient air is absorbed in fibers and converts into liquid state of $K_2CO_3 + H_2O$. This carbon dioxide will be captured and transported through building services, for the future utilization and storage. This research highlights that the chemical flow of the DAC process can be effectively implemented through three distinct architectural design factors: façade modules, and an add-on mechanism for existing buildings and infrastructure. Despite the early introduction of DAC in 1999 (Casaban and Tsalaporta, 2013), its current status remains at the research level and cost demanding, yet to progress beyond industrial applications. However, the paper argues that when broadly applied in buildings powered by renewable energy sources, DAC integration has the potential to mitigate the escalating CO_2 contamination, through ensuring buildings to capture more carbon than they emit, mimicking the principles of photosynthesis from the nature. Thus, the research prioritizes in opening a vision for new concept of sustainable architecture, directly responding towards the global climate issues, and acts as a first stepping stone beyond carbon reduction, towards carbon-capturing architecture.

KEYWORDS: *Direct Air Capture, Potassium Hydroxide, Building Integration, Carbon Mitigation*

I. INTRODUCTION – PROBLEMATIZATION

The escalating global issue of climate change, compounded by the anticipated rise in urban density, as projected by the United Nations (UN), demands urgent attention. Presently, 55% of the global population resides in urban areas, a figure expected to surge to 68% by 2050. This urbanization trend poses a considerable challenge *(United Nations, 2022)*, limiting the availability of space for essential urban green areas crucial for both human well-being and carbon mitigation. The constricted space for accommodating a burgeoning urban population exacerbates the carbon emission crisis, necessitating innovative and space-efficient solutions for the future generation of urbanism and architecture. Traditional methods, such as relying solely on the natural capacity of trees, which is limited to capture approximately 21kg of CO_2 per year *(Boiler, 2022),* fall short in meeting the escalating environmental challenges.

Consequently, there is a critical need to explore and implement advanced technologies, such as Direct Air Capture, to address the pressing issues of increasing carbon emissions, growing urban density, and the diminishing availability of green spaces. Direct Air Capture refers to the use of chemical process to directly extract carbon dioxide from the surrounding atmosphere *(European Commission, Directorate-General for Research and Innovation, 2018).* Furthermore, the IEA *(2022)* has confirmed that achieving carbon-neutrality by 2050 would be difficult without the active contribution of CO_2 capture technology, and the current level of carbon mitigation strategies in architectural industry is insufficient, evidenced by the continuous rise in global CO_2, leaving sector off track to decarbonize by 2050. This paradigm shift requires a re-evaluation of sustainable building practices, transcending the conventional notion of achieving net-zero emissions, towards a more interdisciplinary, comprehensive and integrated approach to mitigate the detrimental impacts of urbanization on the environment.

The research is primarily motivated by the exploration of a novel design approach within various high-density urban conditions, seeking to address a critical challenge: the inadequacy of current carbon mitigation methods in coping with the increasing urban density and global warming. This investigation does not try to establish a complete solution but rather aims to contribute to the academic discourse on sustainable architecture and environmental mitigation strategies, by discovering the existing issues and potentially offering novel insights and integration strategy for the transformative potential of DAC technology in shaping the future of construction practices.

II. METHODS

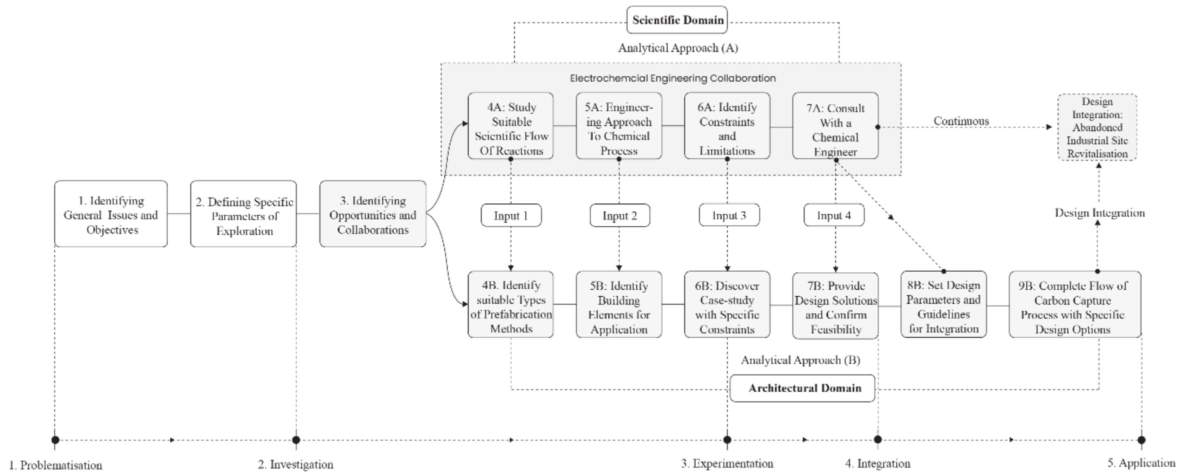

Figure 1. Research Dual Analytical Methodology (Own Image)

2.1. Dual Analytical Approach

The methodology for this research begins with a comprehensive problematization of the issue at hand. Subsequently, a dual analytical approach is undertaken (from 4A and 4B) These fields, namely the scientific and architectural domains, are meticulously investigated in parallel, with the ultimate objective of amalgamating their insights to formulate an innovative approach to the application of carbon sequestration with DAC technology within the built environment. Within the scientific domain, the focus initially rests on the intricate mechanisms how the flow of chemical reactions to capture carbon results in creating potential integration methods to both architecture and engineering.

The study of scientific reactions (4A) of carbon capture process results in identifying the engineer's approach to accommodating the flow of reactions in industrial-scale (4B), which simultaneously influences on identifying suitable building elements for potential application such as façade, modules and cores. Throughout the research process, an interdisciplinary collaboration with a chemical engineer at *TU Delft* is carried out, for identification of constraints, limitations and idea exchange for the feasible building integration. The architectural domain is therefore, acting as a catalyst to further broaden the potentials of the Direct Air Capture technology beyond the industrial or engineering sector.

2.2. Simulations, Calculations and Feasibility Evaluation

Following the dual analytical method, a quantitative method has been implemented to ensure the realization potential of DAC integration. In this process, a real-life industrial application of this technology had to be adapted to acknowledge the existing calculation methods and evaluation factors of the carbon capture results. The paper's primary quantitative data is therefore, imported from a professional engineering journal, "*An air-liquid contactor for large scale capture of CO_2 from air*", published in collaboration by renowned liquid solution-based *Carbon Engineering Ltd*. This journal is a significant input to both calculations and evaluation of design integration, presenting a simple method for optimizing the design of a gas-liquid contactor for CO_2 capture from ambient air. Furthermore, it deeply analyses the reasons why the cost divergence arises from fundamental design choices by reviewing the technology risks and prototype testing in industrial level.

The input of this journal is rather simple but advanced: data of cost optimization model equations and cost optimization variables, values, and units (table 1 and 2) are actively adapted to enable this research to generate a new calculation method adjusted to architectural domain simulations, due to the fact that the existing calculation factors are set for cost analysis and industrial application rather than architectural application. Thus, it has been converted to take fundamental design parameters as new inputs: length and height of air inlet, air travel distance, air velocity (ventilation) and total volume of an integrated DAC system, associated with the way architecture formulates natural and mechanical ventilation and building services.

These parameters are established as new design specifications, which need to be used to ensure the sufficient space, services and energy in façade, building modules, cores and existing buildings. The research proposes the converted calculation method as an adjustment to identify the potential amount of CO_2 captured, cost of operation, energy demand and offset years for a building, which can be used for design optimizations for maximum effectiveness and efficiency with minimum size, cost and energy demand. A further information will be presented throughout the paper, showcasing how the converted calculation method was formed and enables simulations and feasibility evaluation of new design applications, highlighting the novel way of architectural integration.

III. ADJUSTING THE CHEMICAL FLOW OF DAC

3.1. Conventional Flow of Direct Air Capture with Potassium Hydroxide Solution

In the initial phase of the research, a crucial step towards integration involved comprehending the intricate scientific process of the chemical flow in DAC employing potassium hydroxide (KOH) as the primary CO_2 capturing solution. The adopted DAC technology for this integration utilizes *slab geometry contactor*, drawing from components, design, and fabrication methods directly derived from cooling towers *(Holmes and Keith, 2012)*. This technology, commercially available in the industrial sector as *structured packing*, operates on the mass transfer of CO_2 into highly concentrated hydroxide solutions with the support of mechanical fans (figure 3).

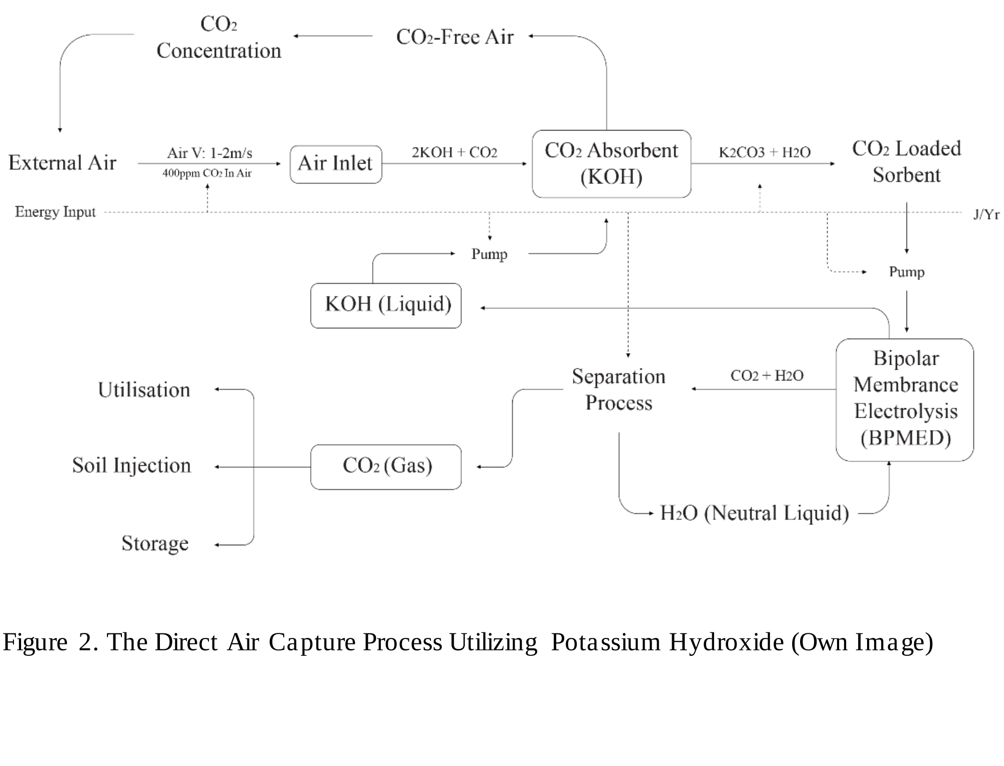

Figure 2. The Direct Air Capture Process Utilizing Potassium Hydroxide (Own Image)

In a simplified depiction (refer to Figure 2), external ambient air is mechanically guided into the system through the horizontal air inlet. The attracted air then passes through a series of hollow-tube fibers soaked in a strong hydroxide solution as a CO_2 Absorbent. During this process, the gaseous form of CO_2 reacts with the KOH solution to form $K_2CO_3 + H_2O$, transforming into the liquid state of CO_2-loaded sorbent. This reaction releases CO_2-free air from the system. The CO_2-loaded liquid is subsequently transferred to an electrochemical unit, converting the captured liquified carbon back to gas through the chemical separation of the CO_2-loaded KOH solution: 2KOH + CO_2. The intricate process of separation occurs from the electrochemical unit, which in this case, utilizes *Bipolar Membrane Electrolysis* (BPMED). The BPMED is the vital electrochemical unit for the successful carbon capture that first accepts the transported CO_2 loaded sorbent and produces neutral liquid (H_2O) and CO_2 through the chemical separation. The produced neutral liquid then returns back to the BPMED to produce a pure KOH solution by receiving a positive potassium (K) ion and negative OH ion. This consequently allows the gas-state CO_2 to be transported for storage, soil injection, or utilization, while the extracted KOH liquid is pumped back into the CO_2 absorbent for a continuous cycle. Quantitative evaluation of this process relies on data from industrial-scale air capture technology (table 1), specifically the slab air-contractor design from *Carbon Engineering Ltd*.

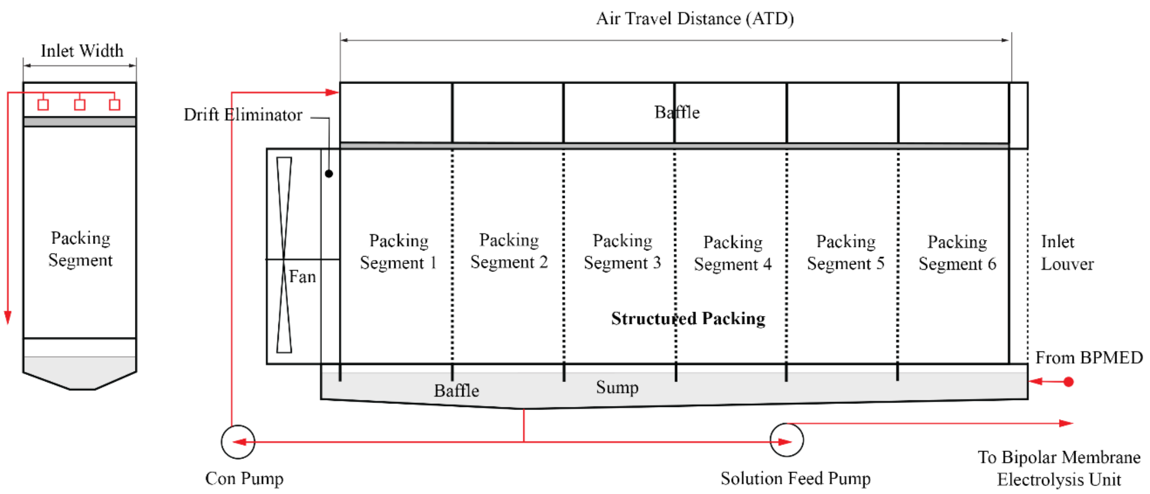

Figure 3. Simplified Process of Slab Geometry Contactor with Structured Packing (Own Image)

3.2. Hollow Fiber Membrane Contactor Reactors

Building upon the established *Slab Geometry Contactor* DAC framework, the fundamental operational principles remain consistent, involving the use of pumps for the circulation of liquid solution and ensuring a continuous airflow through the unit to capture CO_2 via the absorbent segments. A notable departure from the traditional DAC design is the replacement of the packing segment with *hollow fiber membrane contactor reactors*. In this modified configuration, the absorbent solution traverses through porous membrane tubes. The chosen absorbent, potassium hydroxide, demonstrates effective CO_2 capture, releasing CO_2-lean air from the system. This architectural adaptation aims to enhance adaptability within the system's components.

The incorporation of hollow fiber membrane contactor reactors yields a remarkable CO_2 removal efficiency, with claims of up to 99%, surpassing conventional technologies by 30%. Noteworthy benefits include a compact design and the ability to independently manipulate gas speeds, liquid temperatures, and pressures *(IDeCarbon, 2023)*. The compactness and flexibility of flow increases the adaptability of the DAC into complex buildings and the heightened interfacial area facilitates improved mass transfer, ultimately contributing to a self-powered carbon-capturing process. This innovative approach not only enhances the flexibility of the reactors but also optimizes the integration of carbon capture technology into architectural frameworks, marking a significant advancement in the field.

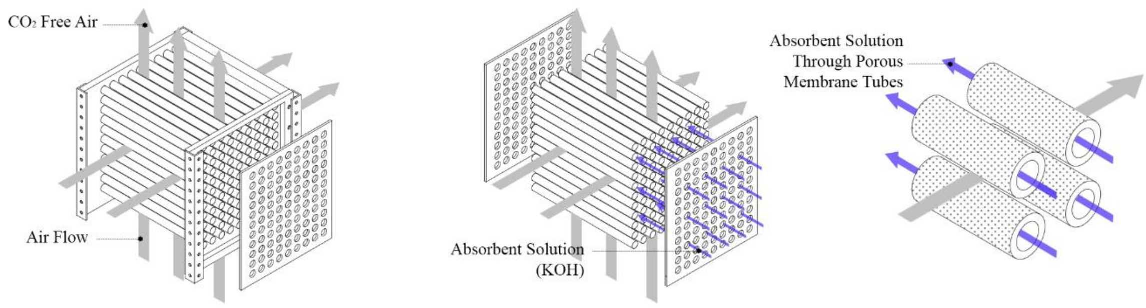

Figure 4. Hollow Fiber Membrane Contactor Reactors (Own Image)

3.3. Adjusting the Flow for Architectural Integration and Potential Impact

The current stage of integrating Direct Air Capture technology within architectural frameworks is situated within the developmental phase, as practical implementation has never been realized. Researchers from Aalto University's Department of Environmental Engineering have classified this integration at a Technology Readiness Level (TRL) of 6, with a low to medium rating in terms of current feasibility for construction and its climate impact within the built environment *(Kuittinen et al. 2023)*. However, there was no feasible attempt to further process the development of integration, and therefore, the research builds a first hypothesis that this level of impact and readiness could be boosted through an appropriate architectural method of design integration. Furthermore, the research aims to set the first example of how several design options and parameters could lead to identifying the relationship of carbon-capturing capacity, cost, energy requirement (solar panels), and CO_2 offset years.

The established chemical pathway of the Direct Air Capture system has been seamlessly integrated into conventional building components for optimal adjustment strategy. As the first stage of the process, maintaining an air velocity between 1-2 m/s is essential for the effective air transport from the air inlet through the hydroxide CO_2 absorbent *(Holmes and Keith, 2012)*. The paper proposes achieving this velocity through natural or mechanical ventilation within the building, performed by the stack-effect and cross ventilation, rather than solely relying on a sizable mechanical fan, commonly found in industrial-scale systems. The strategic placement of DAC-integrated buildings in urban environments further enhances the potential for efficient CO_2 capture relative to energy demand. The elevated CO_2 concentration in urban air streamlines the capture process, reducing the energy input required to extract CO_2 from the ambient air. This addresses a key challenge faced by active industrial-scale DAC systems, typically situated in less populated areas with lower CO_2 concentrations due to installation costs and space limitations in densely populated urban settings. In such urban landscapes, constructing large-scale structures with a singular carbon-capturing function becomes impractical.

In the subsequent phase of the chemical process, CO_2 undergoes a reaction with the hydroxide solution present on hollow-tube fibers absorbent, initiated upon passage through the air inlet. The duration of this journey within the tubes, culminating in the release of CO_2-free air from the system, is formally referred as the *Air Travel Distance* (ATD). The ATD ultimately becomes one of the most crucial design parameters along with length and height of an air inlet, and air velocity towards the inlet. The total volume of the integrated DAC is therefore, discovered by the multiplication of height, length and air travel distance of the system. This calculated volume consequently provides not only the minimum amount of space required for installation, but the amount of CO_2 that could be captured from the specific design specifications. Once the design specifications are defined, the research introduces them as new carbon capture calculation inputs specifically for architectural integration.

Prior to assessing the CO_2 capture potential of the specified design parameters, the research recognized the imperative need to determine the CO_2 capture flux (F). The CO_2 capture flux denotes the rate at which carbon dioxide is effectively extracted from the ambient air through Direct Air Capture technology, quantifying the system's capability to capture CO_2 per unit of time. The calculation formula for carbon capture flux is expressed as (equation 1.1) $F = f_{op} PCO_2 V (1 - e^{-\varepsilon \, SSA \, D \, K_L/V})$ with units in kg/m^2/yr. While the formula originates from *Carbon Engineering Ltd*. and is tailored for industrial-scale applications, this research adapts the engineering specifications and formula directly for architectural integration as an initial framework. This adaptation is justified by the consistency in the fundamental principles of carbon capture processes and the reliability of existing engineered data, which, in this research, remain invariant irrespective of application methods. Thus, according to the basic engineering specifications from *table 2: Cost optimization variables, values and units*, $f_{op} = 2.7 \times 10^7$ s/year, $PCO_2 = 7.3 \times 10^{-4}$ kgm^{-3}, $V = 2$ ms^{-1}, $\varepsilon = 80\%$, SSA = 210m^{2}m^{-3}, and $K_L = 1.5 \times 10^{-3}$ms^{-1} will be substituted to the capture flux formula. The remaining D value in the formula originally represents the depth of the DAC system, and in the case of architectural integration, it will be representing the Air Travel Distance, which will be varied depending on the size tolerance and installation location within a building. Once the Carbon Capture Flux (F) has been obtained, the total available area of air inlet will be calculated with the height and length values. This area is then multiplied by the Carbon Capture Flux (F) value, to obtain the total amount of CO_2 that the specific design could capture in a year.

Table 1. Specified Cost Optimization model equations from Carbon Engineering Ltd

Equation	**Name**	**Formula**	**Units**
1.1	CO_2 Capture Flux	$F = f_{op} PCO_2 V (1 - e^{-\varepsilon \, SSA \, D \, K_L/V})$	kg m^{-2}yr^{-1}
1.2	Pressure Drop in Packing	$\Delta P = D7.4V^{2.14}$	Pa
1.3	Energy for Fans	$E = f_{op} \Delta PV / \eta \, fan$	J m^{-2}yr^{-1}
1.4	Capital Cost	$C_{capital} = C_A + C_{pack} D$	\$ m^{-2}
1.5	Operating Cost	$C_{operating} = EC_{elec} + M\&O \, C_{capital}$	\$ m^{-2}yr^{-1}
1.6	Total Cost Minimization	Min $C_{CO_2} = (C_{operating} + CCF \, C_{Capital}) / FV, D$	\$ per ton CO_2

Table 2. Specified Cost Optimization Variables, Values and Units from Carbon Engineering Ltd

Variable	**Units**	**Value**	**Notes**
η *fan*	%	56	Fan efficiency
C_{elec}	\$ J^{-1}	2.2×10^{-8}	Cost of electricity (80\$ per MW h)
C_A	\$ m^{-2}	3700	Capital cost per frontal area
C_{pack}	\$ m^{-3}	250	Packing and fluid distributor cost
f_{op}	s per year	2.7×10^7	Assumed annual operation fraction (85%)
CCF	% per year	15	Capital charge factor
M&O	% per year	5	Maintenance and operation
ε	%	80	Packing efficiency

PCO_2	Kg m^{-3}	7.3 x 10^{-4}	Mass density of CO_2 in air at 400ppm
SSA	m^2m^{-3}	210	Specific packing area
KL	m s^{-1}	1.5 x 10^{-3}	Mass transfer coefficient
V	m s^{-1}	1-2	Air velocity
D (ATD)	m	5-15 (adjustable)	Packing depth

The diverse design specifications play a significant role in directly shaping the façade design of a building, particularly during the initial conceptual design phase, since these specifications are derived from the size of air inlets from the exterior appearance. These specifications, rooted in the dimensions of exterior air inlets, not only influence the aesthetic appearance but also establish a crucial link between the minimal available space within a building for DAC system installation, the potential CO_2 capture capacity, and the energy demand for system operation. This emphasizes the significance of incorporating DAC seamlessly into building designs, offering not only a convergence of conventional technology with human life but also negating the need for a standalone steel structure dedicated solely to housing the DAC system, as it could utilize diverse building structures.

3.4. Adjusting the "Photosynthesis" with Renewable Energy Sources

Although it is often neglected in the early stages of building design, another vital factor influencing the overall atmosphere, design, and sustainability is energy demand. This factor is crucial not only for determining environmental impact but also for achieving self-sufficiency and cost reduction in building services. This is because the installation of renewable energy sources, such as photovoltaic panels and wind turbines, could contribute to the building's design when applied harmoniously. Furthermore, the amount and sizes of these renewable energy hardware components would always face limitations depending on the available site boundary or open area of a building dedicated to installation. Thus, the integration of a DAC system in buildings would only be feasible if the entire process of carbon capture is self-sufficient, relying purely on renewable energy sources and considering the available space. The research extends the design specifications beyond formulating the potential CO_2 capture capacity by identifying the approximate requirements of renewable sources relative to the capture capacity. The process takes 3 major steps: firstly, the pressure drop (ΔP) calculation based on the air velocity and travel distance within the integrated DAC system. Secondly, energy required per m^2 calculated with the obtained pressure drop result, air velocity, f_{op} (assumed annual operation fraction 85%), and fan efficiency value (η *fan)*. Thirdly, the result of energy per m^2 will be multiplied by the length and height of the air inlet, to generate the value of energy required per DAC module in a building.

I. (Equation1.2) Pressure Drop (ΔP): $\Delta P = D7.4V^{2.14}$, where D is the Air Travel Distance (m) and V is air velocity of 2 m.s^{-1}.

II. (Equation 1.3) Energy/m^2/yr.: $E = f_{op}\,\Delta PV/\,\eta\ fan$, where f_{op} is provided as 2.7 x 10^7s.yr^{-1} and η *fan* is the value of fan efficiency of 56%.

III. (Architectural Integration Equation) Energy/Module/yr.: E x Inlet Length (l) x Inlet Height (h).

The number of these DAC modules will also be varied, and generally, the amount of carbon captured and energy required will be directly proportional to the number of the DAC modules. Despite the aim of utilizing natural ventilation for the air movement, the calculation assumes the use of a mechanical fan. The research identifies that the use of natural ventilation may not always be possible in certain circumstances to achieve the air velocity of 1-2 m.s^{-1} and aims to acknowledge the maximum energy demand for realistic application, rather than the minimum energy demand. Therefore, highlighting that eliminating the use of mechanical fan to achieve the air movement, would only reduce the cost of operation and energy. However, although the use of an electrochemical unit and pumps for hydroxide solution and CO_2 transportation will add to the total energy demand, the research focuses on the operation of the carbon-capturing process only at this level, as the most significant energy consumer.

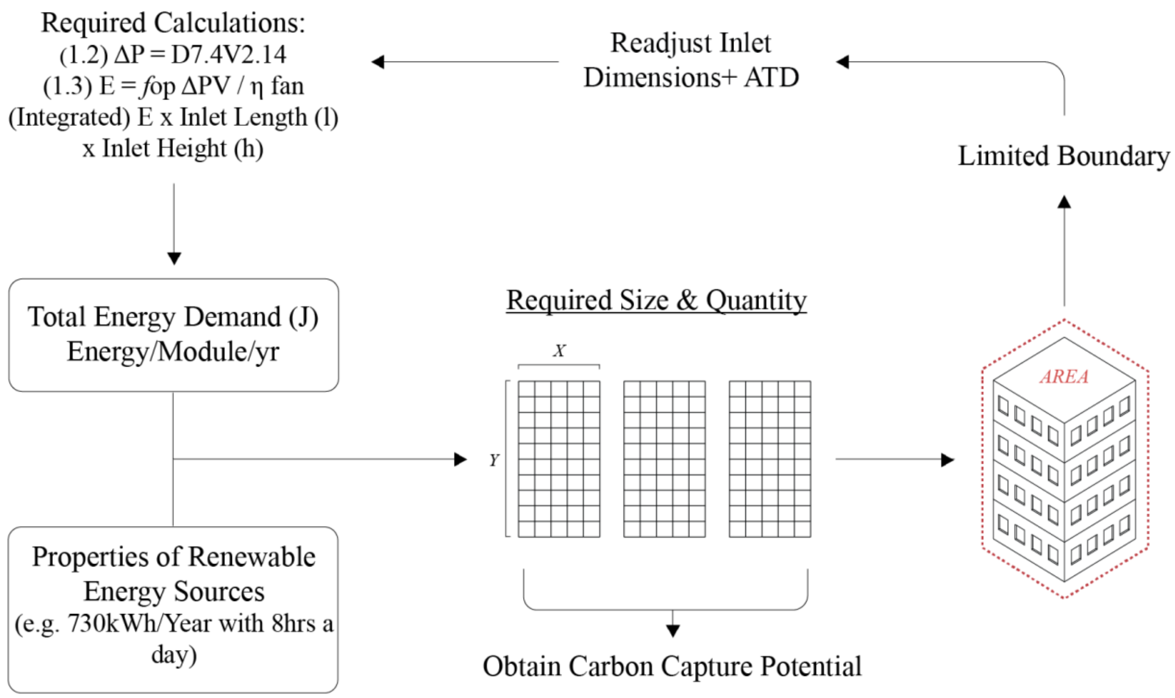

Figure 5. The Process of Optimizing Renewable Energy to Limited Building Boundary (Own Image)

3.5. Available renewable energy inputs and the corresponding CO_2 capture potential

During the research, the simulation is designed to investigate the correlation between available renewable energy inputs and the corresponding carbon dioxide (CO_2) capture potential. The energy input is determined by five key parameters: Air Travel Distance (ATD), Length of Air Inlet (L), Height of Air Inlet (H), and the velocity of wind. As mentioned above, in order to ensure the realism of the system's performance, the simulation assumes the utilization of a mechanical fan to draw external air into the system. The objective of this simulation is to provide guidance on identifying the most optimal and cost-effective parameters mentioned above, following the process shown in figure 5. These parameters directly impact the dimensions and volumes of direct air capture systems integrated into buildings or infrastructure. Given the varying sizes of buildings and the limited available space for renewable energy hardware, it is crucial to ascertain suitable hardware sizes, their number, and their optimal locations. This determination is based on the analysis of *energy demand* data derived from the simulation.

The significance of this analysis lies in the fact that building sizes, site boundaries, and roof areas are constrained. Therefore, finding the most appropriate hardware sizes and configurations is essential to maximize CO_2 capture while minimizing energy consumption. Since the combination of properties of renewable energy sources and total energy demand result in identifying the sizes and quantities of the renewable sources, it is also observable that the CO_2 capture potential is directly proportional to the amount of energy used as displayed in simulation figure 6, and the larger the air travel distance and inlet area, the more CO_2 captured and energy demanded.

The simulation results aim to pinpoint the parameters that yield the highest carbon capture output within the energy constraints of the site by acknowledging the maximum CO_2 that could be captured from the available renewable energy sources output. This information is invaluable for making informed decisions about the integration of direct air capture systems into diverse buildings and infrastructure settings. The design parameters, outlined in Table 3, serve as the foundation for simulating integration methods aimed at uncovering the correlation between energy demand and carbon capture potential. These parameters are categorized into three distinct integration approaches. For applications involving limited space, such as façades with a minimal air travel distance ranging from 0 to 1 meter, the design is optimized. Meanwhile, a slightly larger range of 1.5 to 4 meters is designated for modular units, capitalizing on available open space within suspended ceilings or raised floors. The add-on system, envisioned for implementation on existing buildings and large-scale infrastructure like tunnels, is characterized by a broader integration scope of 4.5 to 7 meters, which is the similar ATD as industrial-scale DAC units, and thus, anticipated to be less expensive. It's crucial to note that while these design parameters are segmented for the sake of simulation simplicity, they are not absolute and can be adjusted to align with the specific requirements of designers.

ATD (m)	Inlet Length (m)	Inlet Height (m)	Velocity ($m.s^{-1}$)	Integration
0	0	0.1	2	Façade Units
0.5	0.5	0.15	2	
1	1	0.2	2	
1.5	1.5	0.1	2	Modular Units
2	2	0.2	2	
2.5	2.5	0.3	2	
3	3	0.4	2	
3.5	3.5	0.5	2	
4	4	0.6	2	
4.5	4.5	0.1	2.5	Add-on System (Industrial-Scale)
5	5	0.2	2.5	
5.5	5.5	0.3	2.5	
6	6	0.4	2.5	
6.5	6.5	0.5	2.5	
7	7	0.6	2.5	

Table 3. Design Parameters Defined for Energy Demand to Carbon Capture Potential Simulation

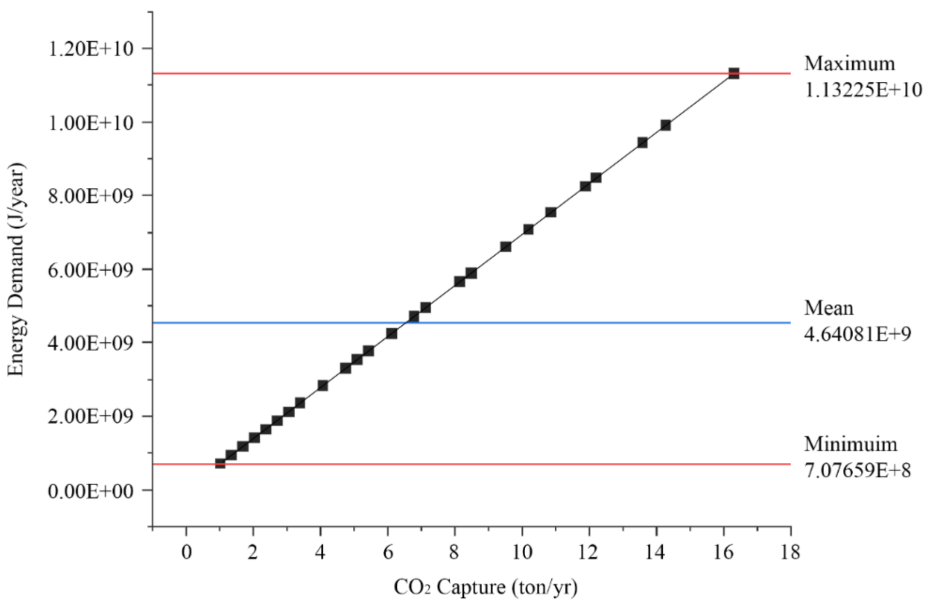

Figure 6. Modular Units Parameters Simulation Outcome (ATD1.5 to 4m)

IV. INTEGRATION AND IDENTIFYING FEASIBLE REQUIREMENTS

4.1.1. Façade Integration Method and Optimization Guideline

The methodological approach for determining the relationship among air inlet dimensions, DAC system volume, energy demand, and potential CO_2 capture capacity provides a comprehensive set of design principles for optimization. The initial integration strategy focuses on façade integration, considering it as the primary aspect influencing the building's exterior. At this juncture, façade is conceptualized not merely as architectural design elements but as colossal CO_2 absorbers reminiscent of the leaves of a tree, actively engaging in carbon dioxide absorption through artificial photosynthesis. The integration method will be elucidated step by step to outline the required process of the architectural integration and highlight the minimum design requirements based on the offset years between 25 to 30 years period and recommended requirements within 10 to 15 years in relation to cost-efficiency. However, setting up the minimum design requirements may not be feasible in certain application scenarios since every building has different materials, sustainability factors, functions and sizes, which all lead to various carbon footprint. Therefore, the research has set a reference with a conventional and existing concrete and steel frame single-floor building with minimum embodied carbon of 3500000 $kgCO_2$ with the total gross internal area of $10000m^2$.

From chapter 3.2, the research has introduced calculation methods for the integration of DAC units into a building, from discovering the carbon capture flux value (*F*) and the carbon capture potential ($tonCO_2$/year) with specific design parameters. In this research the optimization process to identify the minimum and recommended sizes of the integrated DAC units, are carried out by selecting the specified dimensions of the inlet within the range of façade integration ATD of 0-1m as stated in table 3, and compare the offset years, energy demand and estimated cost derived from the calculations of each DAC units with varied design specifications.

Scenario 1: Minimum Requirement (offset years 25<30)			**Building**
Design Parameters	**Values**	**Units**	**GIFA**: 10000 m^2
Air Travel Distance	0.8	m	**Maximum DAC Units Installed**:
Inlet Height	0.2	m	40 each façade
Inlet Length	1	m	(160 units)
Air Velocity	2	$m.s^{-1}$	
Total Volume	0.16	m^3	

Scenario 2: Recommended Requirement (offset years 10<15)			**Building**
Design Parameters	**Values**	**Units**	**GIFA**: $10000m^2$
Air Travel Distance	0.8	m	**Maximum DAC Units Installed**:
Inlet Height	0.4	m	20 each façade
Inlet Length	2	m	(80 units)
Air Velocity	2	$m.s^{-1}$	
Total Volume	0.64	m^3	

Table 4. Design Specifications for Minimum and Recommended Based on Offset Years

Scenario 1 displays the minimum design requirements of the integrated DAC units within the façade and maximized the number of installations based on the total Gross Internal Floor Area (GIFA) of the building provided for the research. The DAC units should be installed every 2.5m to ensure the unobstructed air flow and prevent CO_2-filtered air from returning to the system. Since the total estimated embodied carbon of the building is stated as 3500000 $kgCO_2$, this needs to be divided by the total GIFA value to obtain the embodied CO_2 per m^2, which results in 344.77$kgCO_2/m^2$.

As a next step, carbon capture flux had to be calculated using the formula introduced in advance: $F = f_{op}PCO_2V(1 - e^{-\varepsilon\ SSA\ D\ K_L/V})$, in combination with the imported values from table 2 engineering specifications, the carbon capture flux (F) resulted in 3779.8 kg/m²/year.

After obtaining the carbon capture flux value, the total carbon capture potential will be discovered by multiplying the area of the inlet (l x h), where (3779.8 kg/m²/year) x (1m x 2m) = 760$kgCO_2$/year. Theoretically, the estimated total amount of 760kg of carbon could be captured by a single integrated unit, equivalent to 36 trees a year. Thus, a single integrated unit with the volume of 0.16m^3, is able to save the space required for 36 trees. However, since there are 40 each façade and 160 units in total, 33.5 ton of CO_2 (1447 trees) can be captured per façade and 134 ton of CO_2 can be captured when applied to the entire sides of the building.

The research generates a new formula to confirm the potential of the integrated design by identifying the offset years:

CO_2 Offset Years = (Total Embodied Carbon/m2) / [{(ΣDAC Units) x (CO_2 Capture potential/Unit)}/GIFA]

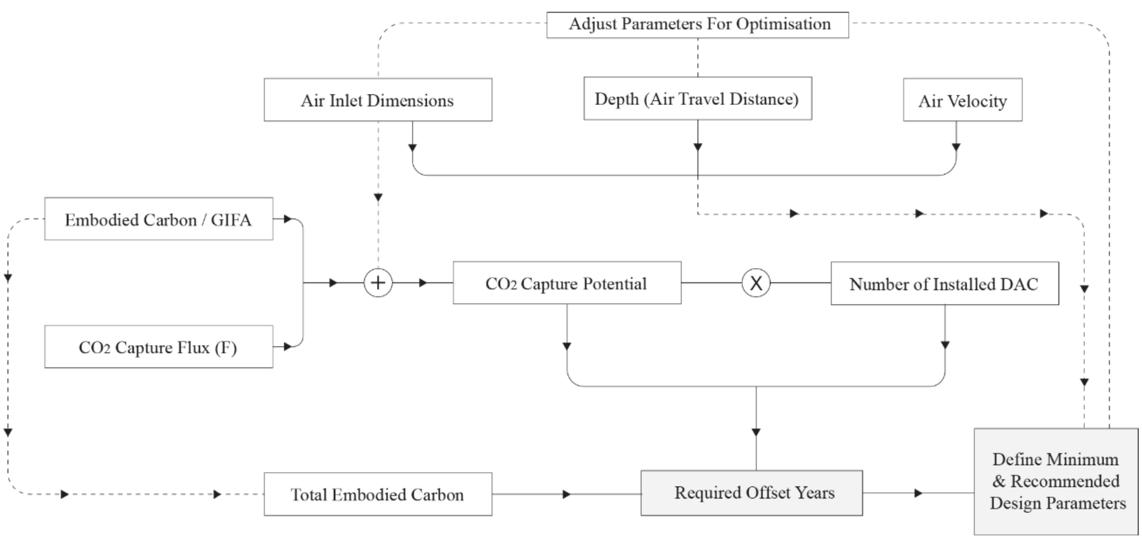

Figure 7. Simplified Design Optimization Method Based on Offset Years

The research underscores the imperative for the quantity of CO_2 captured to surpass the cumulative embodied carbon over the building's anticipated lifespan of 25-30 years. It posits that mere offsetting measures are inadequate in the pursuit of global warming mitigation and achieving carbon neutrality by 2050. The architectural paradigm should navigate towards negative emissions, wherein structures capture more carbon than they emit. The derived values from preceding analyses can be incorporated into the presented formula: (344.77 $kgCO_2/m^2$) / [{(160 DAC units) x (760 kg CO_2/year)}/ (10151.62 m^2)] = 28.7 years to offset. This formula, adaptable to varied scenarios, yields estimated offset durations. In the case of a single-floor building with a minimum DAC volume of 0.16m^3, it is envisioned that the optimal application for carbon offset within a 30-year timeframe necessitates a building façade with dimensions exceeding 100m. Nevertheless, the offset year calculation clarifies that scenario 1 represents the absolute minimum prerequisite for theoretically achieving carbon neutrality within a 30 years span. Consequently, scenario 2 is modeled to attain more pragmatic offset durations by adjusting design parameters, possibly requiring an increase in DAC size while reducing unit numbers to mitigate energy demands, costs, and expedite offset years.

As per Table 4, scenario 2 entails doubling the values of inlet height and length while maintaining the DAC unit depth. Due to unchanged air travel distance from scenario 1, the carbon capture flux value remains constant at 3779.8 kg/m^2/year. However, the carbon capture potential experiences a significant shift due to the altered inlet dimensions: total carbon captured potential = (Capture Flux) x (Length x Height) x 0.001 = (3779.88 kg/m^2/year) x (2m x 0.4m) = 3.02 CO_2 ton/year = 3002 kgCO_2/year. The doubled dimensions of the air inlet result in a single DAC unit capturing an additional 2242 kgCO_2 compared to the integrated DAC in scenario 1. Given the enlarged unit size, a maximum of 20 units can be integrated on a single 100m façade, estimated to capture 60 tonCO_2 per year and 240 tonCO_2 per year from the entire building. Scenario 2 offset years would be (344.77 kgCO_2/m^2) / [{(80 DAC units) x (3002 kg CO_2/year)}/ (10151.62 m^2)] = 14.57 years, just below a 15-year threshold. Therefore, the research contends that scenario 1 parameters represent the minimum, whereas those of scenario 2 are recommended for façade integration within the 0-1m range.

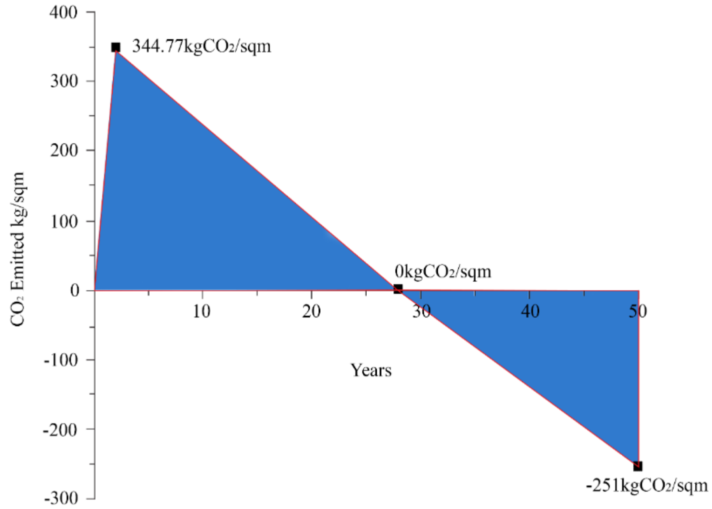

Figure 8. Scenario 1 Offset Years and Absorption in 50 years Simulation

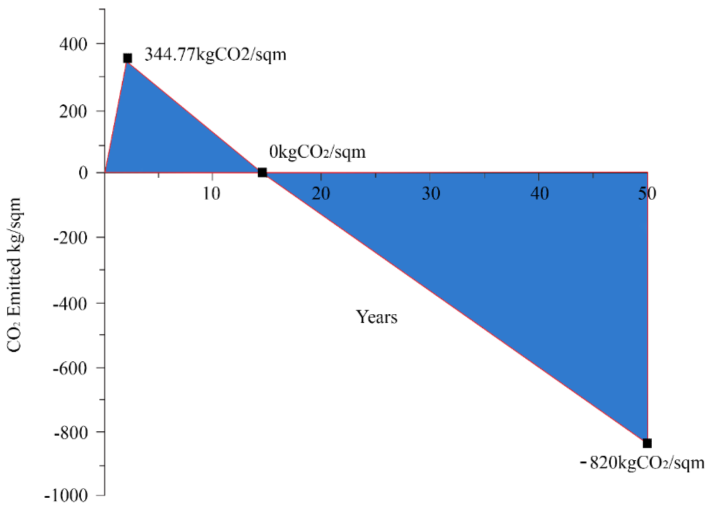

Figure 9. Scenario 2 Offset Years and Absorption in 50 years Simulation

Figures 8 and 9 present a comparative analysis of the outcomes from both scenarios, spanning a 50-year timeframe—the maximum projected lifespan of the building. The evaluation is centered on the relationship between CO_2 emitted and the years required for carbon offset. Evidently, the second scenario emerges as the more robust performer, not only showcasing superior carbon capture potential but also experiencing a substantial reduction in the duration of carbon offset years. The visual representations within the diagrams distinctly highlight that the second scenario significantly outpaces its counterpart in terms of the building's capacity to capture carbon. In this context, the integration of a single Direct Air Capture unit into the façade yields notable results, capturing approximately 820 $kgCO_2$/sqm after achieving complete carbon neutrality. These findings underscore the efficacy of the second scenario in enhancing both carbon capture efficiency and expeditiously reaching a state of carbon offset within the defined lifespan of the building.

4.1.2. The Issues of Cost Involved with Current Technology

From the previous section, the integration and optimization methods have been introduced, comparing both minimum and recommended scenarios by adjusting the design parameters of the integrated DAC units in the building façade. However, energy demand and costs are the real-life constraints and evaluation factors for the feasibility of the integration. For the evaluation of costs involved: capital cost, operating cost, and total cost per year will be carried out by implementing the equation 1.4, 1.5 and 1.6 from table 1 with the values listed on table 2.

Scenario 1: Results from Minimum Requirements (l: 1m, h:0.2m, ATD: 0.8m)			
Equations	**Costs Involved**	**Formula**	**Results**
1.4	Capital Cost	$C_{capital} = C_A + C_{pack}D$	780 $ m^{-2}
1.5	Operating Cost	$C_{operating} = EC_{elec}$ + M&O $C_{capital}$	50 $ m^{-2}yr^{-1}
1.6	Total Cost Minimization	Min $C_{CO_2} = (C_{operating} + CCF\ C_{Capital})$ / FV, D	221 $ per tonne CO_2
Scenario 2: Results from Recommended Requirements (l: 2m, h:0.4m, ATD: 0.8m)			
Equations	**Costs Involved**	**Formula**	**Results**
1.4	Capital Cost	$C_{capital} = C_A + C_{pack}D$	3120 $ m^{-2}
1.5	Operating Cost	$C_{operating} = EC_{elec}$ + M&O $C_{capital}$	200 $ m^{-2}yr^{-1}
1.6	Total Cost Minimization	Min $C_{CO_2} = (C_{operating} + CCF\ C_{Capital})$ / FV, D	221 $ per tonne CO_2

Table 5: The Estimated Cost Involved in Both Optimisation Scenarios

Clearly discernible from the findings, the recommended parameters derived from scenario 2 exhibit notably elevated capital and operating costs. This is primarily attributed to the doubled inlet area and the consequent higher carbon capturing potential associated with this scenario. Specifically, the total cost projection for scenario 1, considering a maximum of 160 units, approximates $124,800 in capital expenses. Conversely, scenario 2, incorporating 80 units, would result in a doubled capital cost of $249,600. Regrettably, the costs associated with both installation and operation are deemed excessively high, underscoring an inherent challenge at the current stage of carbon capturing technology, compounded by supply and technical limitations with smaller DAC sizes than conventional units. It is crucial to acknowledge that these challenges are inherent to the present state of carbon capturing technology and its limited availability. Given that the engineering values utilized in this study are extrapolated from large industrial-scale applications, it is anticipated that the final cost outcomes will undergo significant transformations. This transformation is expected to transpire as the integration of Direct Air Capture units progresses through mass production within the architectural industry, coupled with ongoing developments in DAC unit technology. The research strongly underscores the dynamic nature of these cost projections, emphasizing the need for continuous refinement and adjustment as technological advancements and industrial-scale integration evolve over time.

4.1.3. The Application: Façade Integration

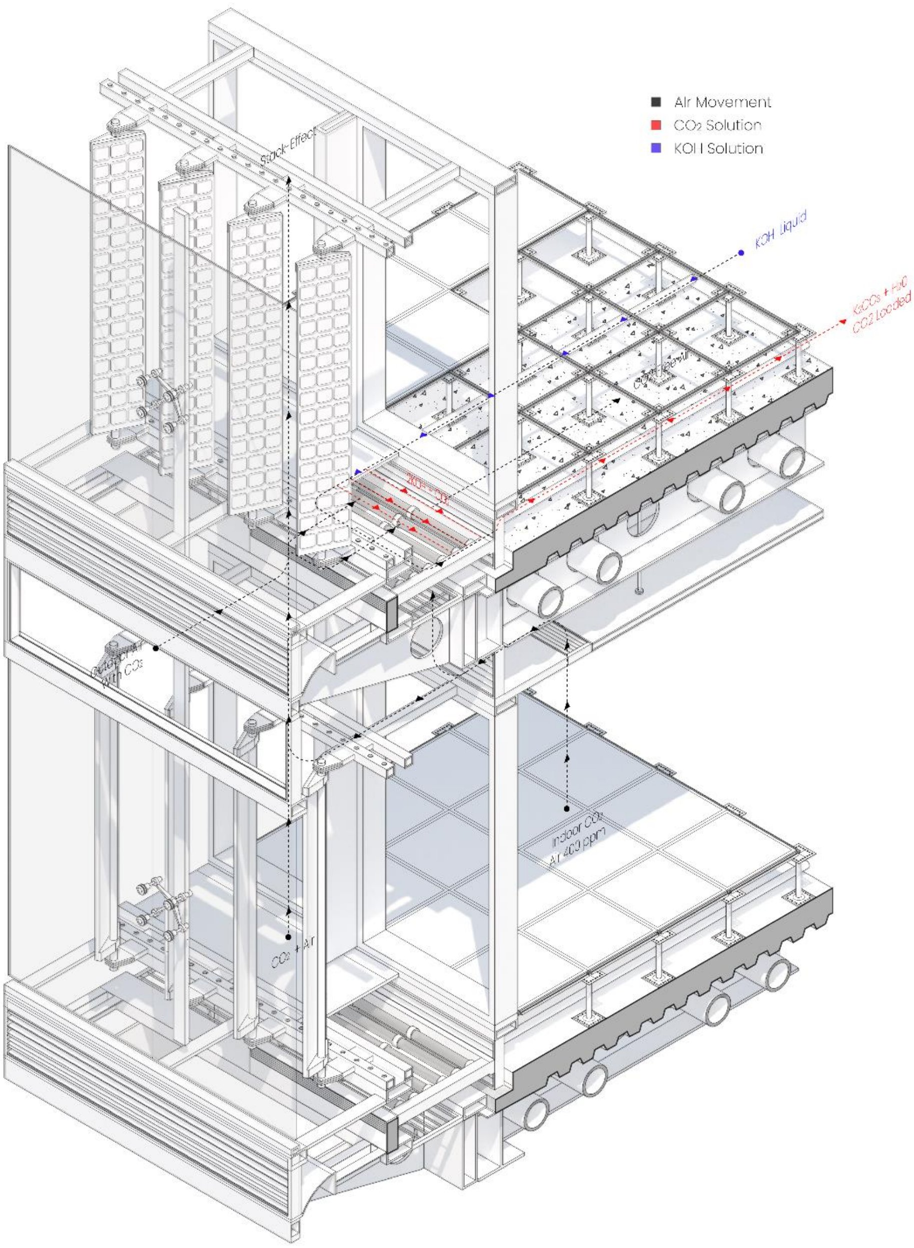

Figure 10. The Application of DAC in Façade System (Scenario1)

The depicted figure illustrates the theoretical implementation of scenario 1, specifically the integration of the façade within a double-skin system. The utilization of a double-skin façade proves advantageous, offering optimal air circulation through the facilitation of cross ventilation and the stack-effect. Importantly, this architectural configuration maintains the thermal performance of the entire building without compromise. The designated gap between the glass panels is identified as an ideal location for the integration of the Direct Air Capture unit and the research highlights the need for raised flooring or suspended ceiling for unobstructed transportation of liquids. Within this visualization, the figure adeptly illustrates how both indoor and external air streams are effectively drawn toward the DAC unit's inlet. This mechanism mirrors the airflow and CO_2 capturing process delineated in Figure 2. The strategic placement within the double-skin system ensures seamless integration, harmonizing the carbon capture technology with the building's architectural design and airflow dynamics. However, the research is only demonstrating an optimal application strategy and certainly, the application could be carried out in different constructions and may be applied differently, while maintaining the direct air capture process (figure 2).

4.1.3 The Energy Requirements and Required Space: Façade Integration

Scenario 1: Energy Demand from Minimum Requirements (l: 1m, h:0.2m, ATD: 0.8m)			
Equations	**Purpose**	**Formula**	**Results**
1.2	Pressure Drop in Packing	$\Delta P = D7.4V^{2.14}$	26.09 Pa
1.3	Energy Per m^2	$E = f_{op}\,\Delta PV / \eta\ fan$	2.52E+09 J $m^{-2}yr^{-1}$
Integration	Energy/Module/year	E x L_{inlet} x H_{inlet}	5.E+08 J. yr^{-1}
Integration	Required PV Panels	E / (kWh×3.6×10^6)	0.19 Panel/module
Required Roof/Site Area (max. 160 units = 30 Panels)			**51 m^2**
Scenario 2: Energy Demand from Recommended Requirements (l: 1m, h:0.2m, ATD: 0.8m)			
1.2	Pressure Drop in Packing	$\Delta P = D7.4V^{2.14}$	26.09 Pa
1.3	Energy Per m^2	$E = f_{op}\,\Delta PV / \eta\ fan$	2.52E+09 J $m^{-2}yr^{-1}$
Integration	Energy/Module/year	E x L_{inlet} x H_{inlet}	2.E+09 J. yr^{-1}
Integration	Required PV Panels	E / (kWh×3.6×10^6)	0.76 Panel/module
Required Roof/Site Area (max.80 units = 60.8)			**103.36m^2**
Adapted Renewable Source Specifications: 400W - 730kWh/year PV Panels			
	Type of Information	**Descriptions**	**Values**
1.4	Dimension	Vital information to respond to available space within provided building boundary	1.0m x 1.7m
1.5	kWh to Joules	Need to convert 730 kWh to Joules as the units of the calculated energy is expressed in Joules.	2,628,000,000 J
1.6	Sun Exposure Time	Higher sun exposure leads to increased efficiency and energy output. Sunlight is the primary source.	8 hours

Table 6: The Estimated Cost Involved in Both Optimisation Scenarios

The outcomes of both scenarios exhibit encouraging results with the modified specifications for renewable energy sources, ensuring that neither scenario surpasses the predetermined roof capacity of the simulated building. Nonetheless, it is noteworthy that the roof space may already be allocated for alternative uses, such as the implementation of an accessible green roof. This circumstance necessitates the consideration of additional space requirements for the installation of Photovoltaic (PV) panels. Consequently, this research advocates for an exemplary application of PV cells integrated within louvers incorporated into the carbon-capturing double skin façade. This approach ensures a continuous and unobstructed flow of air, facilitating an effective carbon-capturing process.

4.2. Modular Integration Method

4.2.1 The Evaluation and Measuring Successful Integration

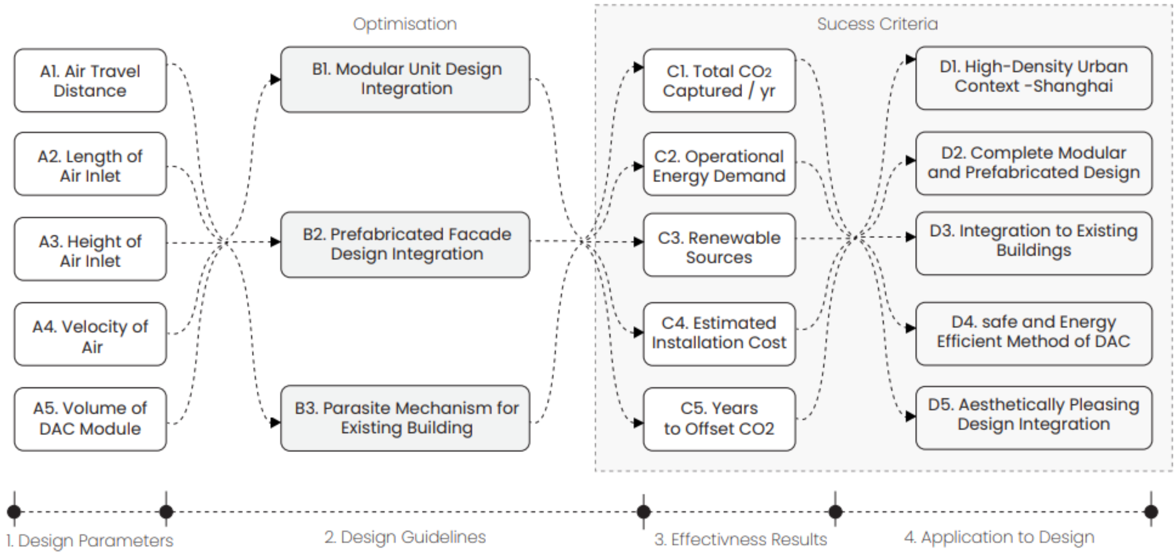

Figure 11. The Optimizations and Success Criteria

The research evaluates the effectiveness of integrated DAC systems under 5 different factors from C1 to C5, measuring both the environmental contribution and the economic feasibility. Thus, figure 11 is used throughout the research to critically assess the potential optimized integration methods as elucidated in prior façade integration simulations. Consequently, the identification of minimum and recommended design requirements is applied in real-life application.

4.2.2 Translating the Chemical Flow into Architectural Modules

The scarcity of space within urban areas has become increasingly evident. Nevertheless, various factors impose constraints on the implementation of novel technologies within built environments. These include infrastructure limitations stemming from pre-existing utilities, the imperative of preserving historical structures, concerns regarding disruptions, and challenges related to accessibility. Therefore, modular construction emerges as a viable solution for the integration of new technologies within the intricate landscape. It provides a controlled and secure environment where the complexities of technology integration can be effectively managed.

The intricate chemical flow inherent in the carbon capture process, delineated in Figure 2, is translated through a synthesis of the building's spatial strategy and services with the comprehensive operational workflow of established Direct Air Capture technology. This research strategically aligns each phase of the DAC process with specific building locations and functions. Analogous to the preceding façade integration, this process is intricately linked to design parameters but, more significantly, contributes to the realization of a comprehensive foundational integration across the entirety of the building. Moreover, the incorporation of DAC into modular constructions anticipates broader applications beyond modular settings, suggesting its potential as an add-on mechanism for both infrastructure and existing buildings, through the extension of air travel distances and augmented air inlet dimensions.

4.2.3 The Integration and Optimisation

Unlike façade integration, the modular construction allows the installation of larger carbon-capturing units, which effectively accelerates the offset years and significantly reduces both operation and capital cost involved, since the larger the system, the closer it is to the existing industrial-scale DAC units. However, it is inevitable that this simultaneously skyrockets the energy demand.

Overall, the integration of DAC in modular construction requires additional ceiling or under floor space through suspended or raised system, and the modules need to be directly connected to façade panels with dedicated air inlets to invite external air to the embedded system. Furthermore, the research recommends that the released CO_2-free air will be guided to the roof through stack-effect ventilation, while transporting captured liquid CO_2 through gravity by placing the BPMED electrochemical unit at the basement of the building. This naturally saves the cost and energy involved during the pumping process of the liquid. However, the potassium hydroxide solution will most likely require a single pump to reach the DAC units placed in the modules and recirculate the carbon-capturing process.

<table>
<tr><th colspan="3">Scenario 1: Minimum Requirement (offset in 2 Years)</th><th>Building</th></tr>
<tr><td>Design Parameters</td><td>Values</td><td>Units</td><td rowspan="6">GIFA:
21 m^2

Maximum DAC Units Installed:
1

Embodied CO_2:
6258 CO_2kg</td></tr>
<tr><td>Air Travel Distance</td><td>1.5</td><td>m</td></tr>
<tr><td>Inlet Height</td><td>0.35</td><td>m</td></tr>
<tr><td>Inlet Length</td><td>1.5</td><td>m</td></tr>
<tr><td>Air Velocity</td><td>2</td><td>$m.s^{-1}$</td></tr>
<tr><td>Total Volume</td><td>0.7875</td><td>m^3</td></tr>
<tr><td colspan="3">Required Ceiling or Floor Height / Module (2.6+0.35)</td><td>2.95m</td></tr>
</table>

<table>
<tr><th colspan="3">Scenario 2: Recommended Requirement (offset in 1 Year)</th><th>Building</th></tr>
<tr><td>Design Parameters</td><td>Values</td><td>Units</td><td rowspan="6">GIFA:
21m^2

Maximum DAC Units Installed: 1

Embodied CO_2:
6258 CO_2kg</td></tr>
<tr><td>Air Travel Distance</td><td>3</td><td>m</td></tr>
<tr><td>Inlet Height</td><td>0.35</td><td>m</td></tr>
<tr><td>Inlet Length</td><td>1.5</td><td>m</td></tr>
<tr><td>Air Velocity</td><td>2</td><td>$m.s^{-1}$</td></tr>
<tr><td>Total Volume</td><td>1.575</td><td>m^3</td></tr>
<tr><td colspan="3">Required Ceiling or Floor Height / Module (2.6+0.35)</td><td>2.95m</td></tr>
</table>

Table 7: Design Specifications for Minimum and Recommended Based on Offset Years

Since the embodied carbon will be varied, the research includes a hypothetical modular project with the dimension of conventional modular housing unit of 21 m^2 with 3m x 7m, constructed with a standard steel shipping container. The module, based on the existing life cycle assessment, has the embodied carbon between 193 to 298 CO_2kg/m^2, resulting in maximum of 6258 CO_2kg for the entire module. For the modular integration research, only a single fully functioning module will be simulated to determine the independent performance. Thus, in case of additional constructions such as cores and corridors, there will be additional embodied carbon. Consequently, the minimum and recommended offset years are set shorter than a large-scale construction (maximum 2 years), as the duration required for CO_2 offset will increase compared to a single module construction. The parameters based on the modular integration stated in table 3 is shown as the air travel distance between 1.5 to 4.5m. Similar to the façade integration, both minimum and recommended parameters are simulated and compared to assess the feasibility of integration based on the values listed in figure 11.

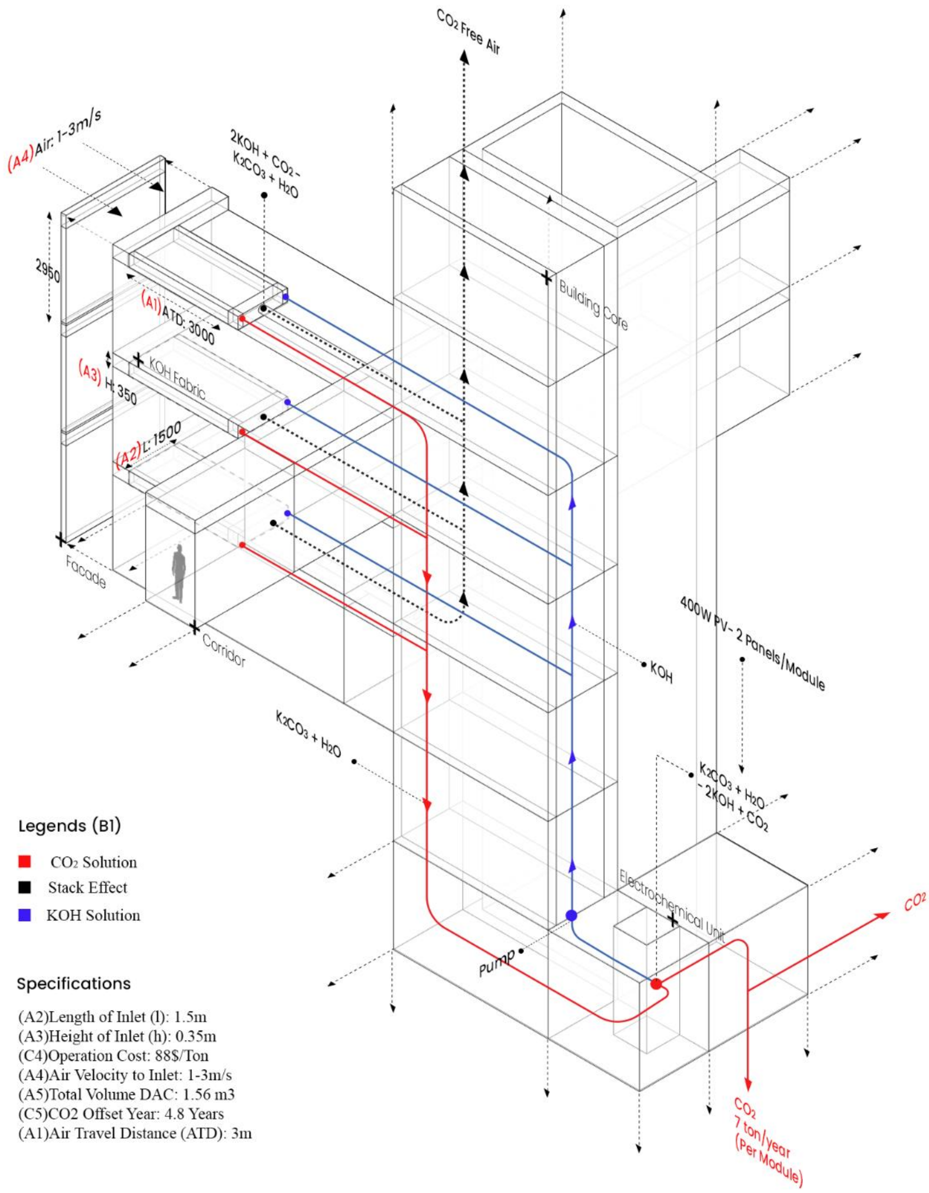

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Figure 12. The Application of DAC in Modules and Full Building Scale (Own Image)

Calculated in the same process as the offset years of façade integration, the carbon capturing potentials of both integration scenarios are identified using the flux calculation: $F = f_{op} PCO_2 V (1 - e^{-\varepsilon\ SSA\ D\ K_L/V})$, where scenario 1 results in the flux of 6788.66 kg/m^2/year with 3.56 CO_2ton/year capture potential and scenario 2 results in significantly higher capture flux of 12408.21 kg/m^2/year with 6.514 CO_2ton/year capture potential. The higher capture flux value has been achieved through the longer air travel distance, that consequently allows the system to capture more CO_2 passing through the DAC unit's KOH absorbent.

Applying the predetermined research formula of offset years, CO_2 Offset Years = (Total Embodied Carbon/m^2) / [{(ΣDAC Units) x (CO_2 Capture potential/Unit)}/GIFA], scenario 1 offset years: (298 CO_2kg/m^2) / [{(1) x (3564kgCO_2/unit)} /21m^2}] = 1.76. Thus, approximately 2 years required to offset the embodied CO_2 of a single module. In comparison, scenario 2 modular container unit offers the offset years of: (298 CO_2kg/m^2) / [{(1) x (6514kgCO_2/unit)} /21m^2}] = 0.96, requiring a full year. Although the single module is able to capture sufficient CO_2 to neutralize the embodied carbon within 2-year time period, the research concludes that the 2-year time as the maximum allowed offset years as the integrated DAC would also be utilized for additional constructions with higher embodied carbon for larger scale application such as existing buildings or mid-rise modular buildings. The investigation takes into account a minimum ceiling height of 2.6m in the context of integrating a Direct Air Capture system. The research findings underscore the necessity of incorporating an additional ceiling space of 0.35m to ensure optimal outcomes in terms of offset years and associated costs. Notably, a reduction in the CO_2 capture potential was observed with smaller inlet heights, yet this did not result in a commensurate decrease in the total cost per ton of CO_2 compared to the 0.35m addition. Furthermore, exceeding the 0.35m threshold for extending the ceiling height was observed to lead to a significant rise in energy demand, compromising the flexibility of the modular system. Thus, from an economic and environmental feasibility standpoint, it is concluded that an additional ceiling height of 0.35m offers the most favorable cost-to-carbon capture ratio.

4.2.3 Costs Involved

Scenario 1: Results from Minimum Requirements (l: 1.5m, h:0.35m, ATD: 1.5m)			
Equations	**Costs Involved**	**Formula**	**Results**
1.4	Capital Cost	$C_{capital} = C_A + C_{pack} D$	2139$
1.5	Operating Cost	$C_{operating} = EC_{elec} + M\&O\ C_{capital}$	161 $ m^{-2}yr^{-1}
1.6	Total Cost Minimization	Min $C_{CO_2} = (C_{operating} + CCF\ C_{Capital})$ / FV, D	135 $ per tonne CO_2
Scenario 2: Results from Recommended Requirements (l: 1.5m, h:0.35m, ATD: 3m)			
Equations	**Costs Involved**	**Formula**	**Results**
1.4	Capital Cost	$C_{capital} = C_A + C_{pack} D$	2336 $ m^{-2}
1.5	Operating Cost	$C_{operating} = EC_{elec} + M\&O\ C_{capital}$	226 $ m^{-2}yr^{-1}
1.6	Total Cost Minimization	Min $C_{CO_2} = (C_{operating} + CCF\ C_{Capital})$ / FV, D	88 $ per tonne CO_2

Table 8: The Estimated Cost Involved in Both Optimisation Scenarios

The research has revealed that, on average, both capital costs and total costs per tonne of CO_2 for modular integration are significantly lower compared to façade integration. The augmented volume and extended air travel distances of the Direct Air Capture units in modular integration bring them closer to the scale of industrial carbon-capturing units, facilitating a more straightforward application compared to smaller DAC units integrated into façade. However, it is crucial to note that the larger volume of DAC units in modular construction results in higher operating costs. Additionally, the findings from the provided table underscore that Scenario 2 not only achieves carbon neutrality within a year but also incurs significantly lower costs for extracting a ton of CO_2 per year compared to the first scenario with minimum requirements. This substantiates Scenario 2 as more suitable for the recommended parameters for modular integration.

4.2.4. The Energy Requirements: Modular Integration

Scenario 1: Energy Demand from Minimum Requirements (l: 1.5m, h:0.35m, ATD: 1.5m)			
Equations	**Purpose**	**Formula**	**Results**
1.2	Pressure Drop in Packing	$\Delta P = D7.4V^{2.14}$	48.92 Pa
1.3	Energy Per m^2	$E = f_{op}\,\Delta PV / \eta\ fan$	4.72E+09 J m^{-2}yr^{-1}
Integration	Energy/Module/year	E x L_{inlet} x H_{inlet}	2E+09 J. yr^{-1}
Integration	Required PV Panels	E / (kWh×3.6×10^6)	0.94 Panel/module
Required Roof/Site Area			**1.7 m^2**
Scenario 2: Energy Demand from Recommended Requirements (l: 1m, h:0.2m, ATD: 3m)			
1.2	Pressure Drop in Packing	$\Delta P = D7.4V^{2.14}$	97.85 Pa
1.3	Energy Per m^2	$E = f_{op}\,\Delta PV / \eta\ fan$	9.44E+09 J m^{-2}yr^{-1}
Integration	Energy/Module/year	E x L_{inlet} x H_{inlet}	5E+09 J. yr^{-1}
Integration	Required PV Panels	E / (kWh×3.6×10^6)	1.88 Panel/module
Required Roof/Site Area			**3.4m^2**
Adapted Renewable Source Specifications: 400W - 730kWh/year PV Panels			
	Type of Information	**Descriptions**	**Values**
1.4	Dimension	Vital information to respond to available space within provided building boundary	1.0m x 1.7m
1.5	kWh to Joules	Need to convert 730 kW to joules as the units of the calculated energy is expressed in Joules.	2,628,000,000 J
1.6	Sun Exposure Time	Higher sun exposure leads to increased efficiency and energy output. Sunlight is the primary source.	8 hours

Table 9: Integration of Solar Panels on Existing Module

The energy demand for an individual modular unit in both scenarios is comparatively modest, given that the first scenario necessitates only one 400W PV panel, while the recommended scenario requires two. This is substantiated by the fact that only 8% of the roof area will be occupied for the modular container unit in the first scenario, and 16% for the second scenario.

4.2.5. The Add-On Modular Mechanism

As shown in advance, figure 12 could also illustrate the complete mechanism of the integrated Direct Air Capture system at a full building scale, employing modular integration. Thus, the add-on mechanism could essentially be an extended version of the modular integration, where the DAC modules and pipes are integrated throughout the existing buildings, keeping the flow of the existing chemical process. Thus, the requirements set for the add-on mechanism is identical to the modular integration. However, although the use of existing buildings significantly reduces the burden of costs and time from constructing a new structure, they are not initially designed specifically for the DAC integration. Thus, the application spectrum is anticipated to be quite narrow, due to the strict restrictions of ceiling height, and limited space for renewable energy hardware, as well as aged building's load-bearing structure.

As part of the research aimed at expanding the application of direct air capture technology in existing buildings, an alternative solution proposes the incorporation of DAC modules into the HVAC system, powered by renewable energy sources. While challenges may arise in finding space for renewable energy installations, leveraging the HVAC system proves to be a time-efficient and cost-effective method for integration. The research outlines a potential strategy for integration by directly attaching the DAC module to the existing HVAC unit, typically located at the top of a building. In this approach, the building's HVAC system pulls air from both the external environment and the interior, capturing high CO_2 levels within the building. The exhaust point of the HVAC system emerges as the optimal location for integrating the DAC module (figure 13). Positioned at the conclusion of the air cycle within the building, this setup allows for the collection of dust-filtered air from both indoor and outdoor sources for purer CO_2 filtering process. Importantly, the integration of the DAC system at the HVAC exhaust point does not disrupt the temperature control or ventilation functions of the HVAC system. Instead, it takes advantage of the existing fan to draw in air with elevated CO_2 levels at a constant velocity. This design not only simplifies the intake of sufficient CO_2 but also contributes to significant energy savings by utilizing a single fan for multiple functions.

Figure 13 illustrates how carbon capture works in practice, showcasing the use of an $8m^3$ DAC unit positioned at the end of the HVAC system. The integration can be fine-tuned based on the available volume designated for existing mechanical ventilation. It's crucial to take note of how outdoor air, supply air, and return air flow to the exhaust, as the DAC unit shouldn't obstruct the necessary airflow that keeps the indoor environment healthy. Additionally, figure 13 portrays the exemplary application of the carbon capturing process, featuring an $8m^3$ DAC unit strategically installed at the termination point of the HVAC system with hollow fiber membrane contactor reactors. This integration is flexible, allowing adjustments based on the available volume allocated for the current mechanical ventilation system. The exemplar integration displays the output result of approximately 35 tonsCO_2/year with ten 400W PV panels to operate fully self-sufficient. Although there is some emission that would occur during the transportation and installation process, the research justifies that the offset-year evaluation is rather pointless, since there is no carbon emission from the actual construction, due the integration into existing buildings. Therefore, the integration into HVAC primarily serves the purpose of financial investment, leveraging CO_2 utilization, or preparing for impending environmental regulations. However, HVAC systems aren't all the same, given diverse air quality requirements stemming from variations in building purposes and sizes. The previous calculations have already covered optimization methods, directly applicable to integrating with HVAC systems. Rather than dictating specific requirements, the research aims to highlight key considerations. Ventilation integration should consistently happen at the end of the air cycle, and installing the DAC unit should not impede HVAC airflow. The captured CO_2 in a liquid KOH solution needs to make its way to the existing BPMED electrochemical unit. Gravity should handle this transportation process, eliminating the need for an extra pump. Placing the BPMED on the ground floor or in the basement ensures smoother transport of harvested CO_2, which can find further use in industry or material production, like making concrete. Overall, the research identifies the integration into existing buildings through HVAC is feasible.

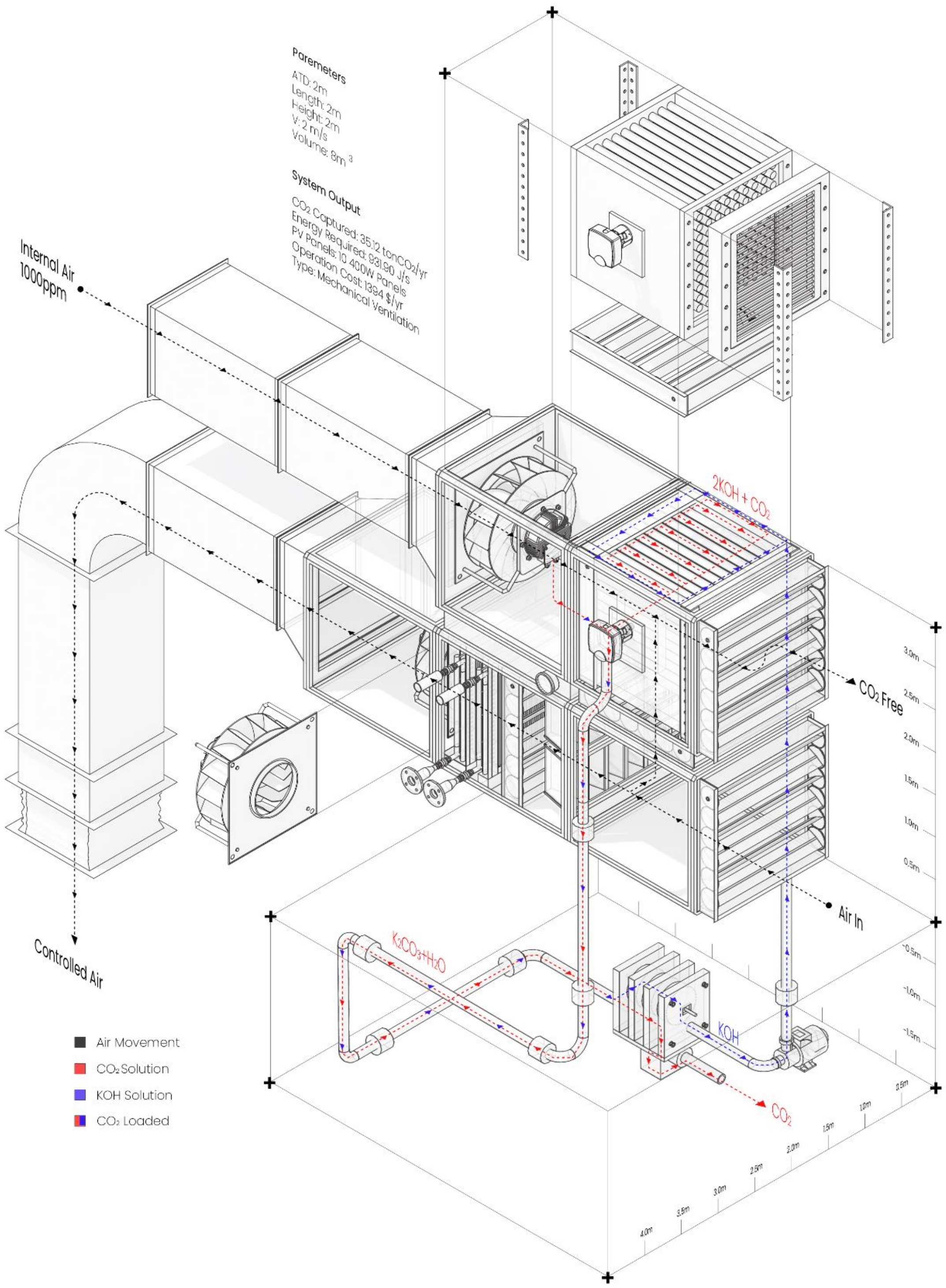

Figure 13. The Application of DAC in Existing HVAC System (Own Image)

V. CONCLUSION

This study underscores the crucial role of decentralizing Direct Air Capture technology to facilitate its seamless integration into everyday life through architectural incorporation. Similar to other engineering and scientific advancements, the widespread application of DAC requires tailored adjustments to its mechanisms, specifically designed for smooth integration into identified target domains. The primary objective of this research is to establish a novel method for incorporating DAC's chemical flow into building components and services, conducting experimental evaluation studies to assess the integrated system's ability to achieve the original goals of carbon-capturing building components and identifying optimized design parameters in relation to energy demand, offset years, and involved costs.

Furthermore, the research focuses on innovative architectural adjustment strategies by utilizing conventional engineering calculation methods derived from the existing DAC Cost Optimization model equations and variables (table 1 and 2). These are then transformed into a new set of formulas for architectural integration, with design-related factors such as façade inlet dimensions and depth serving as the starting point. Through simulations of various design scenarios and feasibility evaluations, the research confidently concludes that integrating DAC into architecture using diverse design methodologies is physically possible, as evidenced by realistic energy demand and feasible carbon offset years for both façade and modular integrations. However, the challenge remains in reducing the integration cost for smaller integration, given that the existing technology is primarily applied on a large-scale industrial level. Decentralizing the technology through architectural integration requires size minimization for flexibility, thereby increasing the capital cost of installation. Additionally, the research acknowledges certain assumptions made due to limitations in existing sources for architectural integration, as buildings exhibit diverse properties.

Despite these challenges, the research provides a forward-looking perspective on the future of architecture, addressing pressing issues such as carbon emissions and global warming. The paper contends that the future of architecture is intertwined with humanity's survival, extending beyond mere design and functionality. From the simulations of modular integration, a single living unit could theoretically capture 6.5 tons of CO_2 per year, and a building with 100 modules could capture 650 tons of CO_2, equivalent to 97.5 hectare of Nordic Forest aged 30 years. While this value may seem modest in comparison to the global emission of 29 gigatons of CO_2 yearly, the study not only offers a positive and self-sufficient solution towards limited urban space for carbon mitigation, but emphasizes that the impact on carbon emissions in the atmosphere must be evaluated on orders of magnitude to be significant. The research aims to perform as a guideline for the future architecture integration of self-sufficient carbon-capturing technology as it covers the methods of holistically assessing the economic, environmental and spatial feasibility.

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