Design Concept Overview

This document provides an overview of the design concept aimed at preventing dust accumulation from affecting solar panel performance in the Sahel region. It highlights the iterative design process, outlines the functions and features of the design, and provides a justification for how it satisfies the requirements.

1. Design Concept Development

The project scope has been refined to focus on the Sahel, a large semiarid region south of the Sahara Desert. This region was chosen due to its projected population growth in the next few decades–which will significantly increase energy demand– and its considerable untapped solar energy potential [1].

To generate potential solutions for cleaning dust from solar panels while minimizing anchoring bias, an initial round of diverging employed diverse brainstorming techniques. Strategies included the lotus blossom technique *(3.1.2 lotus_blossom_final)* and reverse brainstorming *(3.1.3 reverse_brainstorming)*, ensuring a broad exploration of concepts without premature commitment to a single approach. Many designs were inspired by common everyday items. For example, the conveyer belt was inspired by the reusable paper towel rolls *(3.1.6 reference designs, 4)*. SCAMPER was then applied to combine initial concepts to more complex ideas, addressing individual design weaknesses. This approach strengthened areas that may otherwise be lacking such as accounting for different environmental conditions, facilitating both diverging and converging in the design process simultaneously. Four designs were formed from SCAMPER *(3.1.5 SCAMPERed Ideas)* and a fifth design that was unique from the other four but created during the initial diverging was chosen *(3.1.4 initial_list_of_ideas)*. The top five designs were: the Wind Barrier, the Conveyer Belt, the Roomba, the Waterfall and the Vortex Cannon *(3.2.2 top5_converge)*.

Five viable designs underwent evaluation through a structured converging process (3.2.2 top5_converge). Artifacts from the converging process are documented and found in the 3.2.1 Converging Charts spreadsheet. Requirements were ranked using a pairwise comparison matrix ***(Requirements Pairwise** tab)* which assessed each requirement based on its alignment with the NGOs while considering the unique stakeholder needs in the Sahel. A preliminary Pugh Chart *(**Pugh Chart 1** tab)* was then used to compare the five designs against these requirements. This initial evaluation led to the elimination of the **Waterfall** design, which violated the water use constraints and was subpar in the energy use requirement. Then, a detailed **Measurement Matrix** was developed to inform our second Pugh Chart *(**Pugh Chart 2** tab)*. This Pugh Chart revealed that both the **Roomba** and the **Vortex Cannon** designs were underperforming in the key requirements of removing dust and minimizing energy consumption, resulting in their elimination. A final Pugh Chart was utilized (***Wall and Roller Direct Comparison*** tab) to directly compare the two remaining designs. While the **Conveyor Belt** demonstrated advantages in several secondary metrics, the **Wind Barrier** outperformed in all four of the highest priority requirements. Based on this assessment, the **Wind Barrier** was selected as the final design.

2. Final Design Concept Summary: SANDR

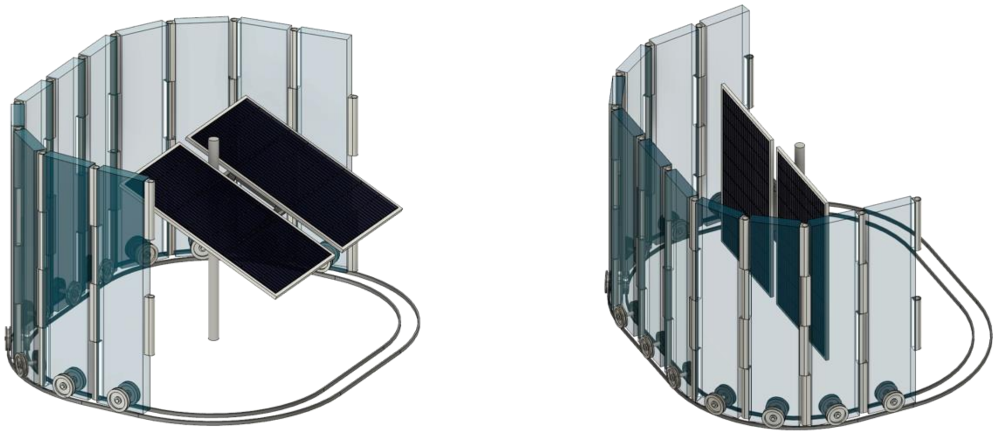

Figure 1: A CAD model of the design that highlights the transparent barrier on a rounded square track. The solar panel in the middle is on a singular stand allowing for it to tilt along the x and y axis. Model on the left shows the position during high winds and the model on the right shows the position when it is inactive at night.

SANDR consists of a tilted solar panel surrounded by a moving barrier. The barrier will block the dust particles from the wind, preventing the solar panels from becoming dirty. In addition, the solar panel can change which way it is facing with respect to the cardinal directions (referred to henceforth as its orientation), as well as its vertical tilt angle (referred to henceforth as tilt), to prevent as much dust as possible from landing on the panel while still allowing optimal sun coverage. It can also tilt to be perpendicular to the ground at night to remove any dust that made it past the barrier. A control system will capture wind and rain data from various sensors positioned near the moving barrier and combine it with the sun's position to find the best position for the barrier and solar panel.

This design is motivated by a few key facts from the academic literature which are highlighted in 2.1.3 Design Concept Overview Source Extracts. Firstly, it was found that most dust deposited on solar panels is carried by wind [2]. However, the deposition of dust is highly dependent on wind conditions; winds of more than about 2 m/s can clear dust off the panels if they are facing directly into the wind [3][4][5]. Rain intensity has a similar relationship to deposition rate: heavy rain washes dust off the panels, but light rain instead turns it into mud and increases adhesion through a process called cementation [5]. Panel tilt also affects deposition rate, with about a 60% difference between horizontal and 60 degrees from the horizontal. This design takes all these factors into account to find the configuration of tilt, orientation and barrier position that minimizes dust deposition while maximizing solar radiation. The key advantage is that this is a preventative design rather than one that acts to clean after the solar panel is dirty.

The barrier is 1.4m and made up of panels of strong, transparent material that will rotate on a square track with rounded corners surrounding the solar panel. Choosing a height of 1.4m allows for a balance between being tall enough to block the dust while also not casting shadows on the solar panels and thus hindering their absorption ability [6]. Due to the solar panels being on the roof of buildings, the space restriction on the roof led to the decision to make the track square shaped rather than a circle as the track would then encircle a smaller area. The barrier will be 1 m away from the wall to minimize shadows on the solar panel while still effectively blocking the dust particles from the wind [6]. The track will have sand deflectors along it to ensure the track does not get jammed and thus hindering the movement of the barrier.

2.1. System Architecture

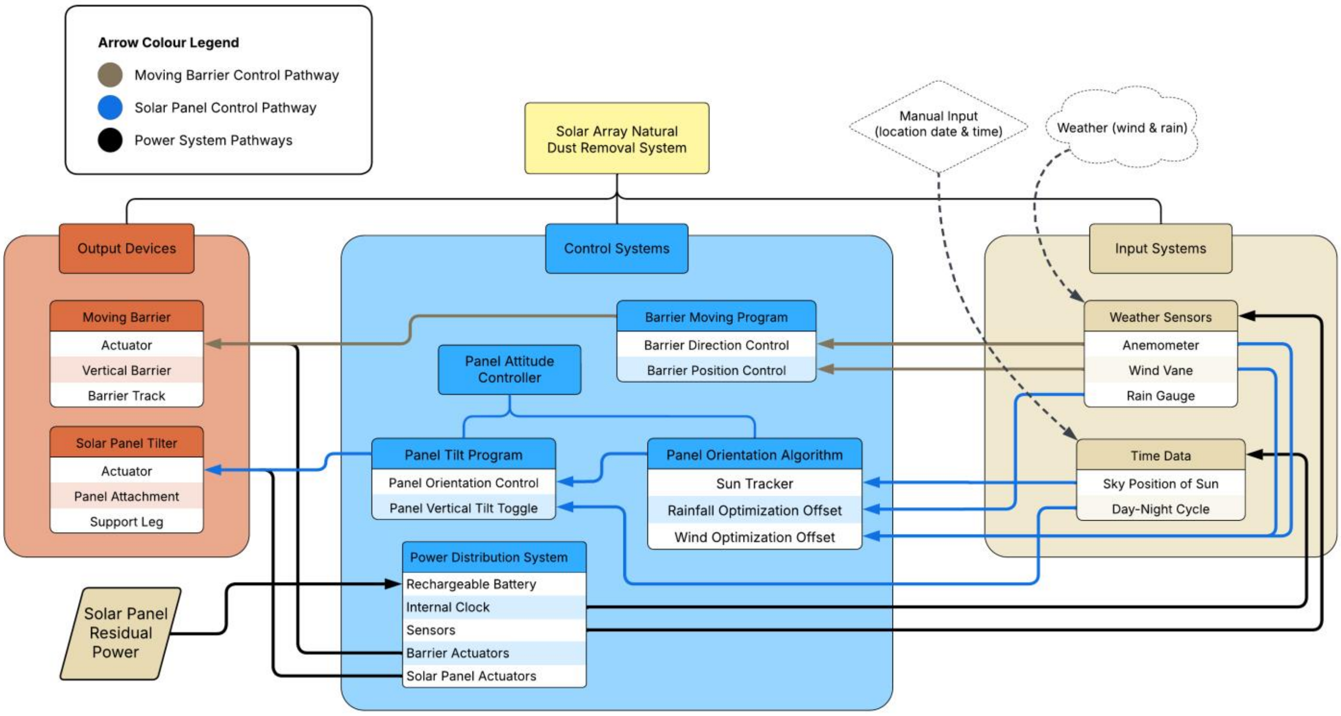

Figure 2: A system architecture diagram showing the three high level systems followed by the subsystems within and how they connect to each other.

The system consists of three main components: input system, control system, and output devices, as seen in Figure 2. Three sensors–an anemometer, wind vane, and rain gauge–are deployed outside the track to measure wind strength, wind direction, and rain intensity respectively. These sensors eliminate the need for external weather forecasts and Wi-Fi for weather information. This not only provides more precise and local information but is well-suited for off-grid deployment in regions such as the Sahel. Additionally, an internal clock tracks time, allowing the system to determine the sun's position for optimal panel configuration.

The control system processes sensor data and onboard knowledge about the sun's position to determine the optimal configuration for the solar panel and the barrier. The Panel Attitude Controller governs the adjustment using two main subsystems: the Panel Tilt Program and Panel Orientation Algorithm. While the tilt program controls the vertical angle of the solar panel, the orientation algorithm determines how the panel should be angled in response to wind direction, rainfall, and sunlight. The tilt angle will be calculated by balancing between the latitude-based optimal angle for solar radiation and the angle that minimizes dust accumulation [3][7]. The Barrier Moving Program manages the movement of the barrier, adjusting its position to either block incoming dust or allow wind to clear dust from the panel surface. Power for these systems is supplied by a Power Distribution System, which includes a rechargeable battery, ensuring operation even in low-light conditions.

The solar panel tilter adjusts panel's tilt and orientation based on the control system calculations while the moving barrier–equipped with actuators and a track–repositions itself depending on the environmental conditions. These components work together to dynamically adjust based on the real-time weather conditions and time of day.

2.2. System Behaviour

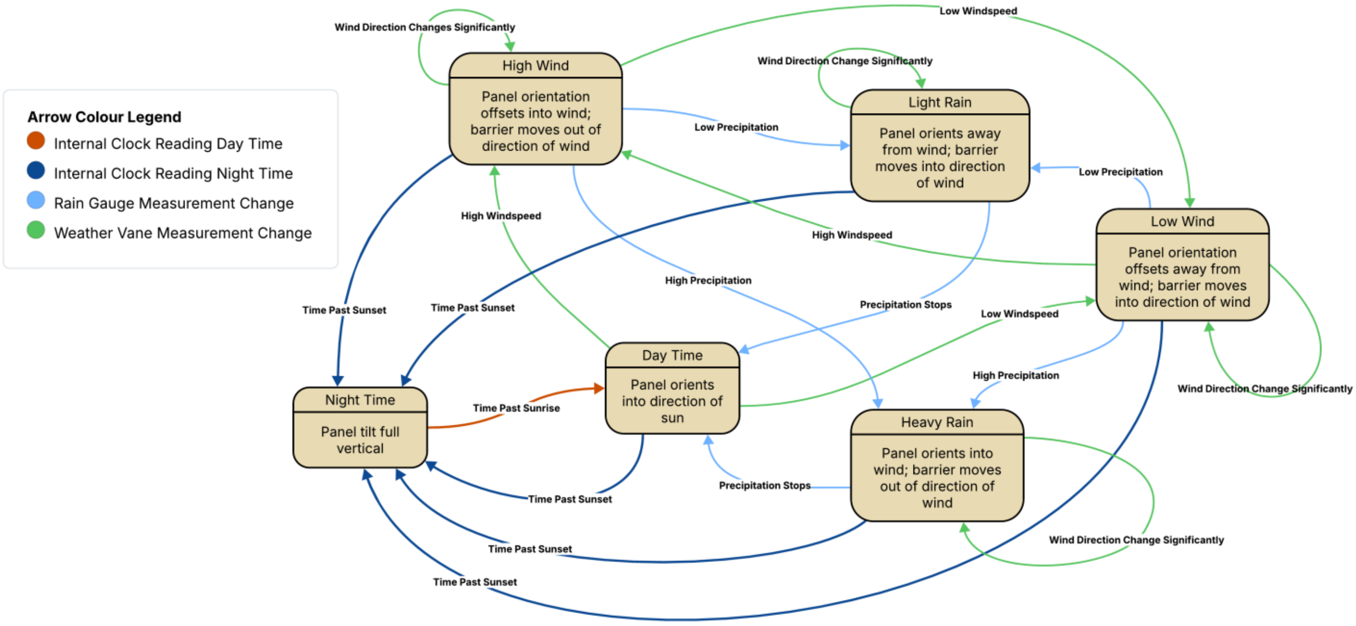

Figure 3: A state diagram that shows how the design will react and change position accordingly based on multiple external weather conditions.

At the module level, the system consists of three modes as illustrated in Figure 3.

1. **DAYTIME OPERATIONS**
    a. **LOW WIND:** Barrier moves **into** wind to block dust, panel orients to the optimal balance between towards the sun and away from the wind and tilts for optimal balance between maximizing sunlight and minimizing dust deposition.
    b. **HIGH WIND:** Barrier moves **away** from wind to let wind remove dust, panel orients to the optimal balance between towards the sun and towards the wind and tilts for optimal balance between maximizing sunlight and minimizing dust deposition.
    c. **LIGHT RAIN:** Barrier moves **into** the wind; panel orients and tilts away from wind to minimize dust sticking to wet surface.
    d. **HEAVY RAIN:** Barrier moves **away** from the wind, panel orients and tilts towards wind to maximize rainfall dust cleaning.
2. **NIGHTTIME OPERATIONS**
    a. Panels tilt to a full vertical position to reduce dust accumulation and allow for most dust particles that made it past the wall during the day to slide off. The barrier remains positioned based on the last wind conditions.
3. **TRANSITION PHASES:**
    a. **SUNRISE:** Panel shifts from vertical to tracking the sun and wind.
    b. **SUNSET:** Panel returns to vertical position.

2.3. Connection to Requirements

Requirement	Justification
FO-1/PO-1: Remove and/or prevent particles that obstruct sunlight	By preventing dust from accumulating in the first place rather than cleaning it after it has already accumulated, this design keeps panels dust-free for a long period of time. Changing the tilt of the solar panel to optimal angles can reduce the deposition rate of dust on the panels up to 60%, and changing its orientation relative to the wind can reduce it by up to 50% [3]. The combination of the barrier and tilt of the panel can reduce dust deposition up to 95% in alignment with the requirement [6][3]. While the device focuses on preventing dust from accumulating, it also allows for dust removal by facing solar panels towards the wind at certain threshold speeds, and facing them towards rain in heavy rain. These higher wind speeds and heavy precipitation can blow away or wash off particles that have accumulated on the surface [5].
FO-2: Mitigate effect of their presence on sunlight contacting solar panel	Placing the barrier 1 m away from the solar panel results in a maximum of 20% coverage of panel area [6], although in most scenarios the barrier will not be placed directly between the solar panel and the sun. Transparent materials typically block 10-15% of light, so at most 3% of solar energy will be blocked [8]. Furthermore, as the device uses an algorithm to find the optimal angle between the sun and wind, it will improve panel irradiance relative to a stationary panel.
FO-3: Be able to operate in various weather conditions (humidity, temperature, wind)	The design should function in any humidity, temperature, and wind levels. While humidity and temperature can increase adhesion of dust to the surface of the panel, the prevention techniques still work. The design also adapts to various wind angles and speed to find the optimal position of the barrier and panel.
PO-2: Minimize resource consumption required for operation (water and energy)	The design minimizes water consumption by relying on dust prevention methods, such as panel tilt and barriers leading to water consumption of 0L/day. Additionally, it utilizes naturally occurring rainwater to remove accumulated dust, reducing the need for additional resources. The design minimizes energy consumption by using the wind and rain to remove particles. It only needs to adjust position a few times a day when there are significant wind and solar changes. Solar panels in Africa generate 16,236 kJ/day [9] with an average loss of 21.57% (<3500kJ) [10] due to dust. Estimations of a 0.07-meter-cubed barrier moving 8m/day leads to energy consumption of 6.4kJ (See measurement matrix), much less than the energy saved, meeting this constraint.
PO-3: Operate quietly	The main noise concern for this design is the barrier moving along the track. For comparison, battery-powered trains create noise levels of 60dB [11]. With the design's significantly lower size and speed, the noise level is estimated to be around 48dB (see measurement matrix).
PO-4: Be easy to use	After the initial setup, the design is fully automated, removing the need for user interaction. The setup only requires the user to input their time and location which is simple and not time-consuming.
PO-5: Be easy to maintain	On average, frequently used garage doors, similar to the design's barriers, need to be serviced twice a year [12]. With services typically being under 5 hours [13], it keeps maintenance times under the constraint of 26 hours per year.
PO-6: Be safe for the user	The barrier is fairly heavy, so its movement could pose a safety hazard. However, the barrier will move much slower than 6 inches per second (approx. 50%), in accordance with safety standards for garage doors, ensuring user safety [14]. While the barrier does not have sensors for force exerted like garage doors, it is unnecessary since the barrier is moving slowly rather than closing and will not crush objects.

3. Works Cited

[1] J. Mueller-Kaler, "What future for the Western Sahel?" *Atlantic Council*, 21 November 2021 [Online]. Available: https://www.atlanticcouncil.org/in-depth-research-reports/report/what-future-for-the-western-sahel/

[2] J. Wang, W. Hu, Y. Wen, F. Zhang, and X. Li, "Dust deposition characteristics on photovoltaic arrays investigated through wind tunnel experiments," *Scientific Reports*, vol. 15, no. 1, Jan. 2025, doi: https://doi.org/10.1038/s41598-024-84708-2.

[3] Younes Noorollahi, A. Saboonchi, and Ali Akbar Alemrajabi, "Experimental study of factors affecting dust accumulation and their effects on the transmission coefficient of glass for solar applications," vol. 112, pp. 466–473, Nov. 2017, doi: https://doi.org/10.1016/j.renene.2017.05.050.

[4] M. M. Dagher and H. A. Kandil, "Computational prediction of dust deposition on solar panels," *Environmental Science and Pollution Research*, vol. 30, no. 5, pp. 12545–12557, Sep. 2022, doi: https://doi.org/10.1007/s11356-022-22993-y.

[5] L. Wan, L. Zhao, W. Xu, F. Guo, and X. Jiang, "Dust deposition on the photovoltaic panel: A comprehensive survey on mechanisms, effects, mathematical modeling, cleaning methods, and monitoring systems," *Solar Energy*, vol. 268, pp. 112300–112300, Jan. 2024, doi: https://doi.org/10.1016/j.solener.2023.112300.

[6] B. Raillani, D. Chaatouf, M. Salhi, S. Amraqui, and A. Mezrhab, "Effect of wind barrier height on the dust deposition rate of a ground-mounted photovoltaic panel," *Sustainable Energy Technologies and Assessments*, vol. 52, p. 102035, Aug. 2022, doi: https://doi.org/10.1016/j.seta.2022.102035.

[7] D. De Rooij, "Solar Panel Angle: how to calculate solar panel tilt angle?," *Sinovoltaics - Zero Risk Solar™*. https://sinovoltaics.com/learning-center/system-design/solar-panel-angle-tilt-calculation/

[8] S. Guzman-Puyol, J. J. Benítez, and J. A. Heredia-Guerrero, "Transparency of polymeric food packaging materials," Food Research International, vol. 161, p. 111792, Nov. 2022, doi: https://doi.org/10.1016/j.foodres.2022.111792.

[9] M. Armstrong, "The future looks bright for Africa's solar energy output," World Economic Forum, Jul.12, 2022. https://www.weforum.org/stories/2022/07/africa-solar-power-energy-sustainability-climate-change/

[10] S. Lasfar et al., "Study of the influence of dust deposits on photovoltaic solar panels: Case of Nouakchott," Energy for Sustainable Development, vol. 63, pp. 7–15, Aug. 2021, doi: https://doi.org/10.1016/j.esd.2021.05.002.

[11] "How Battery Hybrid Locomotives Help to Reduce Noise Pollution, " Clayton Equipment, https://claytonequipment.co.uk/battery-hybrid-locomotives-reduce-noise-pollution/

[12] M. Houchin, "How Often Do Garage Doors Need Maintenance?," Doorvana, May 1, 2021. https://www.doorvana.com/blog/how-often-do-garage-doors-need-maintenance

[13] "How long does a garage door repair typically take?," All About Garage Doors, Aug. 9, 2024. https://callallabout.com/blog/how-long-does-a-garage-door-repair-typically-take/

[14] *Safety Standard for Automatic Residential Garage Door Operators*, ANSI/CAN/UL 325, 2021. Available: https://www.federalregister.gov/documents/2016/04/07/2016-07552/safety-standard-for-automatic-residential-garage-door-operators