Final report - DC Smart House 5

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November 5, 2024

1 Introduction and Problem Statement

Since 1890s alternating current (AC) has been the system for electricity supply to homes. We are still using AC as our energy supplier for houses via electricity grid nowadays. However, most of the devices that are currently used in resident houses, for example: phones, laptops, and EV chargers, are built for direct current (DC). Therefore AC has to be converted to DC before using it, resulting in conversion losses. This inefficiency will become even bigger in the future, with an increase in energy use by devices at home and the generation of renewable energy at residential homes by solar panels or other renewable energy sources.

Political conflicts and financial instability in major fossil fuel-producing countries, may cause unstable energy prices. Also, the global stock prices in oil, gas, and coil companies may have a significant impact on the prices of electricity produced from fossil fuels. This results in significant price fluctuation of fossil fuels in energy supply market. In the worst scenario, people have to compromise on some primary necessities in life, as they will not be able to pay the electricity bill otherwise.

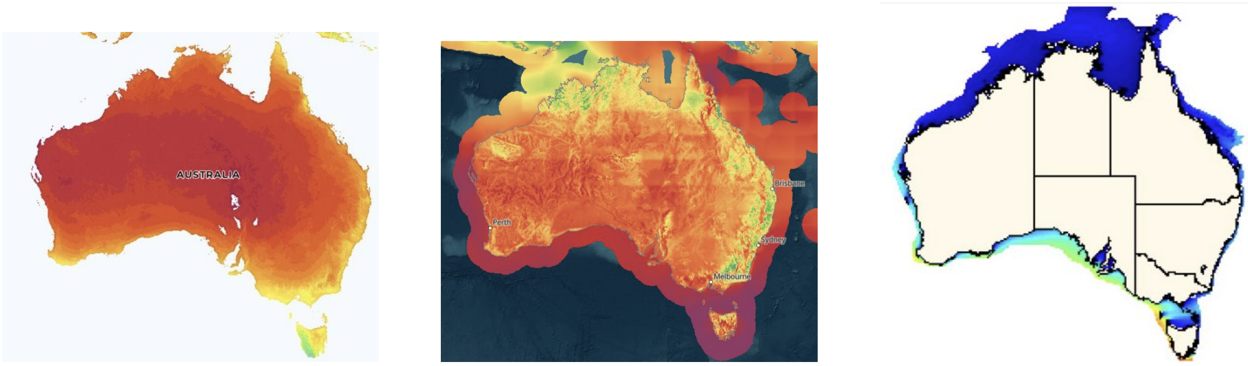
As fossil fuels are not renewable, at some point in time they will begin to deplete. In that case, other energy sources must be used in order to run society. All of the above-mentioned points resulted in the problem statement.

1.1 Problem statement

AC energy sources are less efficient due to conversion losses. Energy produced from fossil fuels may give rise to high and unstable energy prices, as well as global climate change. Therefore, a self-sustaining neighborhood of financially viable smart DC apartment buildings, optimized with complementary renewable energy solutions must be developed.

1.2 Location

This document explores the construction of a full DC house in western Australia. In Australia, one of the highest available wind and solar energy densities worldwide can be found [Zah10]. Also, the government steers towards a higher injection of renewable energy in the grid. Another benefit of Australia is that the policies and standards of the government are easily accessible and written in English making it clear what rules will apply to the DC house. Within Australia, the intensity of wind, solar, and wave energy were compared. Figure 1a shows the solar irradiance in Australia. It can be seen that the western part of the country has the highest solar irradiance. Figure 1b shows the wind energy intensity in Australia. The south and southwest of Australia have the highest wind energy intensity. Lastly, Figure 1c shows the wave energy intensity. A lighter color means a higher wave energy intensity. The highest wave intensity is found in southern Australia. When these three maps are placed on top of each other, a sweet spot can be found in the southwestern, near Perth. Since the DC house shall be built at a location close to a mature city, Perth was chosen as the final location.



(a) Solar energy intensity map Australia [Atl24a]

(b) Wind energy intensity map Australia [Atl24b]

(c) Wave energy intensity map Australia [HH10]

Figure 1: Renewable energy sources in Australia

2 System Definition Matrix

The first step in solving the problem statement is defining the System Definition Matrix (SDM). The SDM ensures that the project addresses all the significant aspects of feasibility, scope, and performance.

The relevant stakeholders who affect or are affected by the project's progress were found out. These stakeholders are: future residents, current neighborhood and entrepreneurs, government, grid operators, wildlife, contractors and constructors. Based on the stakeholders, scoping and bounding is done for the SDM. The scoping includes needs, objectives, and criteria. The bounding includes constraints, parameters, and variables.

2.1 Key Points

The SDM is formulated on the basis of following the below key points derived from the problem statement in Section 1.1.

1. **Conversion losses:** Efficient energy conversion and lower energy losses can be realized by focusing on DC systems. This improves the overall efficiency and reduces the conversion losses.
2. **Cost effective:** By generating the optimum amount of energy inside the property to sustain the load demand of the building and transmitting the excess energy to an external grid, no extra energy has to be bought from the energy market and this makes the entire system much more cost-effective.
3. **Renewable energy sources:** The dependence on fossil fuels can be resolved by using renewable energy sources such as solar, wind, and tidal energy. This results in a lower CO2 emission and contributes less to the greenhouse effect.
4. **Regulated DC voltage:** The DC voltage profile should be regulated in a manner so that the installed appliances function at optimum efficiency levels, ensuring low chances of voltage fluctuations, breakdowns, and electrical fire hazards.
5. **Durability:** The project should use sustainable and durable building materials to reduce repair costs and reduce carbon footprints of production of building materials.

The entire SDM can be found in the Microsoft Teams channel.

3 Trade-off

As stated in the problem statement in Section 1.1, the main focus is on making sure the energy used in the house is purely renewable, while at the same time remaining affordable. Even when electricity prices rise due to political conflicts or due to running out of fossil fuels in the future. Secondly, the conversion losses of converting voltages should be minimized to use as much of the produced energy as possible. That is why three trade-off concepts are chosen that all have an internal DC house grid, to make sure there are no AC-DC conversion losses inside the local DC grid. An important factor to consider, however, is the ability to deliver excess power to the main AC power grid. This leads to three different concepts:

- Concept 1: Use of the traditional AC grid connection as it is used nowadays. At all times energy can be delivered to or taken from the grid. Its main advantage is to be able to balance energy demand and supply. This is done with a bidirectional AC-DC converter between the house and the grid so the house itself can run fully on DC. The energy conversion will result in conversion losses.
- Concept 2: Only a DC-AC inverter (unidirectional) from the house to the grid to be able to sell excess energy to the AC grid. This also has the advantage that it prevents the need for a lot of batteries, it just needs a lot of production of energy.
- Concept 3: Fully off-grid DC house. The main advantage of this concept is that no energy is wasted at all. Excess energy is stored. All of the produced energy is used inside the house and there are no AC-DC or DC-AC conversion losses. This system can have some difficulties with balancing the supply and demand during the day.

The most important criterion for this project is the reduction of conversion losses to make sure no energy is wasted. Another important criterion is the self-sustainability of the building, as the building shall be independent of external power resources and the ability to fully optimize the building to the renewable energy sources arises. Lastly, to be able to live in a modern building, the inhabitants must have access to electrical energy to provide for the primary living conditions under normal operation. Therefore, the reliability of the electrical energy system must be ensured. These and other criteria were placed in a table.

A balanced and reliable energy system is fundamental in building a (fully DC-powered) residential home. Simplicity of the overall apartment design results in fewer difficulties during design and construction. Still, if a system is more complex it does not have a direct influence on the problem statement, therefore resulting in a lower weight. The criteria described in the above paragraph are more important with respect to the problem statement than some other criteria and thus have a higher weight. An overview specifying the weights of the trade-off table can be found below:

3. The criterion will have almost negligible influence on the decision of which concept is going to be chosen. The criterion does not have a connection to the problem statement.
4. The criterion will have low importance in the decision-making. The criterion does not have a direct connection to the problem statement.
5. The criterion has a minor influence on the concept of decision-making. The criterion has an indirect unimportant connection to the problem statement.
6. The criterion has a neutral influence on the concept of decision-making. An unimportant connection to the problem statement.
7. The criterion has a moderate priority in choosing which concept is more favorable. There is a connection of insignificant importance observable between the problem statement and the criterion.
8. The criterion has a measurable impact on the concept of decision-making. There is an observable connection between the criterion and the problem statement.
9. The criterion is of high importance in choosing which concept is more favorable. There is a strong connection between the criterion and the problems stated in the problem statement.
10. The criterion is extremely important for the concept decision-making. The criterion is connected to the utmost important problems in the problem statement.

Table 1: Trade-off table for main concepts

Criterion	Weight (1-10)	Concept 1: (0-5)	Concept 2: (0-5)	Concept 3: (0-5)
Weather independency	3	5	3	1
Scalability	6	2	4	3
Available knowledge	8	4	4	2
Power balancing	10	5	4	2
Efficiency	10	3	4	3
Share of renewable energy	10	3	5	5
System lifespan	8	2	4	4
Electrical safety	9	3	3	4
Self sustaining	10	1	4	4
Simplicity of the electrical system	4	5	5	4
Reliability of energy	10	4	3	3
Ease of maintenance	8	2	3	4
	Sum:	**298**	**368**	**323**

The trade-off table is shown in Table 1. In the trade-off table, concept two has the highest score and shows the most potential as a solution to the problem statement. It scores high at especially scalability since the designed building can be built near mature cities with access to similar renewable energy sources. Secondly, for concept two the whole house runs on DC and excess power is being delivered via a converter to the grid preventing wasting the produced excess energy. This results in a lower waste of the total produced energy resulting in a total higher efficiency. The conversions between AC and DC in the first concept result in higher conversion losses. Concept three only relies on battery storage, meaning that excess power is lost when the batteries are fully charged, resulting in a lower efficiency. Concepts one and two rely on sharing energy with an external system and within the designed system, such that all the generated energy can be used. Both concepts two and three do not rely on an external system and can fully function self-sustaining. Taking all these considerations into account, concept two has the highest overall score and is therefore the concept that lies at the foundation of the project.

4 Requirements

To define the requirements it is necessary to rely upon a list of stakeholders (as already stated in Section 2). Starting from the problem statement in Section 1.1, stakeholders have been identified in all those subjects that are actively or passively involved in the project, like future residents (example of an active stakeholder) and wildlife (example of a passive stakeholder). Requirements are defined by measurable, and executable specifications of a system describing how the needs will be met. The requirements are formulated in accordance with the system definition matrix and respective stakeholders.

Some of the important requirements for all stakeholders are listed below. The complete list of requirements can be found in our Microsoft Teams channel.

A. Future residents

- **Living space**: To make sure all of the residents have a spacious and comfortable living space, the apartments shall come with three bedrooms, a kitchen with a ventilation system, and a bathroom. (**Requirements A.5, and A.21**)
- **Ease of road connectivity**: The building shall be located in proximity to major city routes and highways. (**Requirement A.7**)
- **Safety and hygiene:** Every floor shall have emergency exits, assembly points and exit emergency plans. In addition to this, the residents must have access to clean drinking water with a reserve of two weeks in case of emergencies. (**Requirements A.13, and A.17**)

- **Power consumption management:** The energy generation must take place within the property using complementary renewable energy sources. One electric vehicle charging port must be allocated for each apartment. (**Requirements A.24, A.25, and A.26**)
- **Surplus energy and financial returns**: The surplus energy produced shall be able to be transferred to the grid for financial returns. (**Requirement A.29**)

B. Current neighborhood and entrepreneurs:

- **Architectural design**: The building shall be designed in a manner that aligns with the architecture and aesthetics of the neighboring construction structural design.(**Requirement B.1**)

C. Contractors and constructors:

- **Use of high-quality material**: The high quality of construction materials is a key requirement for both contractors and constructors. Therefore the building must be made of materials that are durable, readily available, and economically sustainable. The minimum lifetime of the materials shall be 150 years. (**Requirement C.2, C.3, and C.4**)

D. Government:

- **Construction compliance**: As a general requirement all the solutions designed for the project must be aligned with local laws and regulations. (**Requirement D.2**)

E. Grid operator:

- **Power grid capability**: The power grid shall be capable of transferring all produced excess power. (**Requirement E.1**)

F. Wildlife:

- **Reducing noise levels**: Wind turbine installation shall integrate noise mitigation strategies to limit disturbances in marine and terrestrial ecosystems. (**Requirement F.1**)

4.1 Requirements conflicts

Having different stakeholders means there will arise conflicts between requirements, as the different stakeholders have different interests. In a self-interaction matrix, all the requirements are validated against each other, to find out whether they are conflicting. In the self-interaction matrix, a 'g' indicates no conflict, a 'm' indicates there might be a conflict between two requirements, and a 'c' indicates a conflict between two requirements. Some conflicts are described below, the entire self-interaction matrix can be found via Microsoft Teams channel.

Conflict 1

- Requirement A.22: The yearly energy consumption of a household shall not be more than 16.5 MWh per year (i.e. energy generation > 16.5 MWh per year per household).
- Requirement A.25: Power shall be generated inside the property.

These requirements conflict, as the property will house 60 households, and the area will be roughly 1200 m^2. This area will be more or less fully occupied by the apartment building, and it is not possible to generate the amount of energy specified in requirement 22 on the property of the apartment building, as requirement 25 states. A possible solution to this conflict is to cooperate with local energy initiatives (for instance multiple apartment buildings) to place offshore wind turbines or tidal power sources.

Conflict 2

- Requirement C.1: The building materials must be accessible and available.
- Requirement C.2: The apartments must be built with durable materials such that the complex has at least a lifespan of 150 years.

These requirements might give rise to a conflict, as durable building materials might not be accessible or available at the time of construction. A possible solution would be to postpone the start of construction (this is undesirable) or to decrease the maximum lifespan of the materials in Requirement C.2.

After investigating solutions for all possible conflicts, the new self-interaction matrix contains 20 potential conflicts ('m') and 4 conflicts ('c'), whereas the initial matrix contains 30 potential conflicts and 13 conflicts. The conflicts that cannot be solved easily are mainly involving potential natural disasters (tsunamis, hurricanes, etc.) and the potential conflicts mainly involve the style of current houses in the neighborhood where this apartment building will be built. The new self-interaction matrix can be found in the 'After resolving conflicts' sheet in the original self-interaction matrix file in our Microsoft Teams channel.

5 Functional decomposition

From the requirements, several system functions were devised (Section 4). Three high-level functions, in cohesion with the problem statement (Section 1.1), were created encompassing self-sustainability, comfortable living, and connecting the building facilitating data transfer. Comfortable living addresses, among other things, the financial viability of the apartments reducing financial stress. Connecting the building makes it for example possible to implement an energy management system that can optimize the energy production, storage, and load distribution.

Function 1: The building relies upon self-sustainability

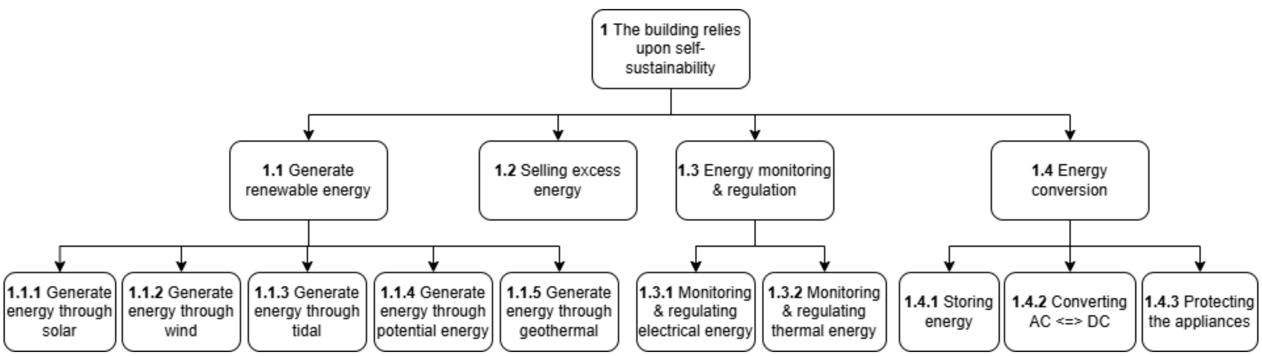


Figure 2: Functional decomposition of high-level function 1

From requirements A.22 and A.24 in Section 4, it followed that the energy generation should cover the entire energy demand in a whole year and the energy should be generated from renewable sources (the first sub-function). To address the financial viability by providing a source of income, generated excess energy can be sold to the grid. A multitude of means can already be assigned to this sub-function and is not broken down further into smaller sub-functions. Thermal and electrical energy within the house should be monitored such that the thermal and electrical energy flows can be optimally regulated. Energy conversion within the building will be applied to store energy, convert between AC and DC and protecting the appliances.

Function 2: The building is comfortable to live in

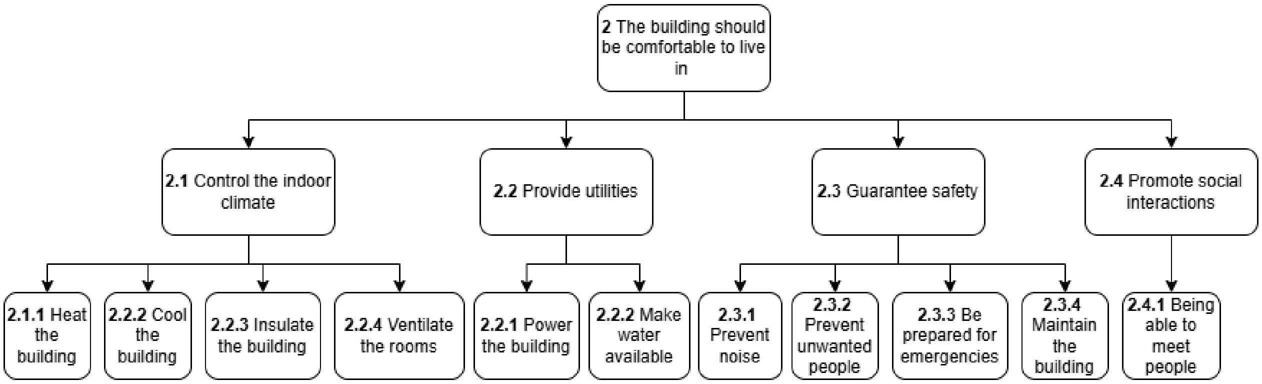


Figure 3: Functional decomposition of high-level function 2

A multitude of requirements were combined to define the high-level function of the building being comfortable to live in. From this high-level function, four sub-functions were generated, that deal with climate control, providing utilities, safety, and social interactions. These sub-functions can all be broken down in smaller sub-functions. This high-level function is especially of importance such that people want to live in the building. All these functions together will make a future resident feel comfortable in the apartment building and like living there.

Function 3: The building is connected internally and externally

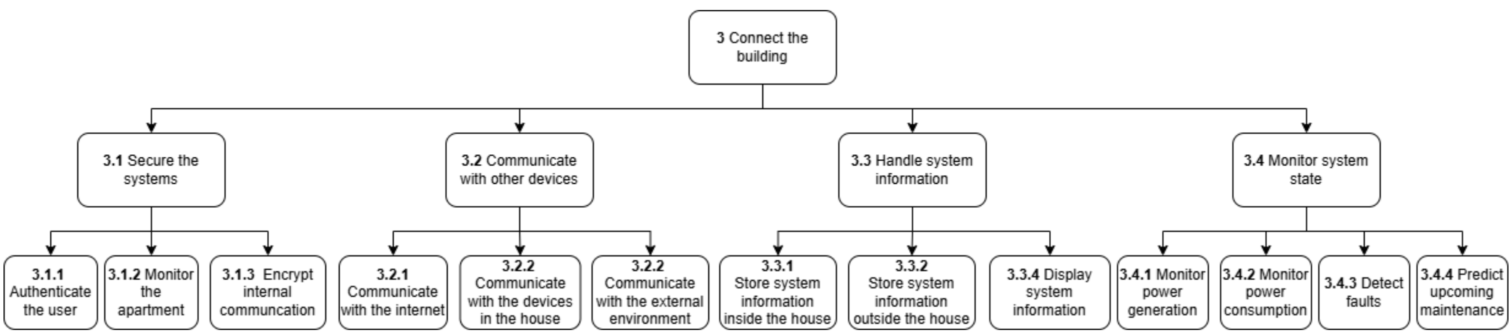


Figure 4: Functional decomposition of high-level function 3

This high-level function is derived from the optimization problem specified in the problem statement. Data transfer is needed to control the energy management system and to make communicate happen between appliances and energy generation sources. Also, without residents being able to communicate or having a connection to the outside world, live in the apartment will have limitations. The connection of the building entails the digital security of the building: user authenticating, monitoring, and encrypting of internal data. Moreover, communication with other devices, internal and external, and system information handling is performed in this function. The last sub-function is monitoring the system state, which takes care of monitoring the power generation, consumption, fault detection, and maintenance prediction.

5.1 Morphological analysis

For the functional decomposition discussed above, morphological analysis is used to identify all the possible solutions/means to the main function and its sub-functions. Means criteria are defined to evaluate the possible means and select the best means. The means meeting the criteria the best are highlighted in green, the average means in yellow, and the least suitable means are marked in red. The means in green are all suitable for the project and define our solution space. The complete morphological analysis table can be found in our Microsoft Teams channel. Each main function is broken down into sub-functions and its possible means are explained below. Means criteria adopted for each function are also elaborated.

Function 1 will be discussed in more detail than the other two, as it directly addresses our problem statement. While the other two functions are also important, these are not significant enough to require the same level of detail.

Function 1: The building relies upon self-sustainability. The criteria for the morphological analysis of the first function are given below.

- **Sustainability:** The solution should have the least negative environmental impact and include renewable and eco-friendly practices such as reducing CO2 emissions by promoting renewable energy and using energy-efficient appliances.
- **Feasibility:** The solution should be practical and implementable, which means it can be implemented within time without costing too much.
- **Efficiency:** The solution should be power efficient in energy generation, storage, and conversion. The efficiency should be higher than that of the other solutions.
- **Space:** The solution should take up minimal space in the constraints of the building.
- **Protection:** The solution should have safety measures and protection circuits to safeguard the system.

The aim is to ensure that the DC house not only generates renewable energy, but also maintains a stable, safe, and efficient energy system.

1. **Sub-function: Generate renewable energy**

   The most important sub-functions are about the generation of electricity using solar, wind, and tidal energy. Geothermal and potential energy are not discussed here since they are out of the scope of this project.

   (a) **Generate electricity through solar energy**: One of the most optimal means is the monocrystalline solar panels since they are highly efficient [Sug20], durable, affordable, lightweight, and suitable for large-scale installations. Whereas options like organic photovoltaic solar panels have lower efficiency, shorter lifespan, and faster degradation; for this reason, they are not selected.

   (b) **Generate electricity through wind energy**: Onshore wind turbines are one of the most optimal means since they are easy to install and are cost-effective [ETOR20]. Offshore wind turbines are not selected because they are costly to install and are less accessible for repairs

   (c) **Generate electricity through tidal energy**: Tidal stream generators are selected as the best means because they are reliable, renewable, and a consistent energy source. Dynamic tidal power is complex and unproven on a large scale [Wik24] and hence it is not selected.

2. **Sub-function: Selling excess energy**

   (a) **Means of selling**: Peer-to-Peer (P2P) energy trading is selected as the best means because it enables consumers to buy and sell excess energy directly [ZNS+24]. On the other hand, DC microgrid systems are not selected because of their high initial setup cost compared to the other trading models.

3. **Sub-function: Energy monitoring and regulation**
   The sub-functions under this are:

   (a) **Monitoring electrical energy**: The best solution is smart metering, as it provides real-time monitoring of electricity usage and ensures automatic and accurate meter readings [AAAK22]. On the contrary, smart plugs and smart power strips are not selected as they monitor and control only individual devices.

   (b) **Regulating heat energy**: Solar thermal heating is considered the best solution since it directly captures the heat from the solar panels and has higher energy efficiency with minimal electricity usage [KAEHAH22]. Heat pumps are not selected since they rely on electricity to transfer heat, which increases the running cost.

4. **Sub-function: Energy conversion**
   The sub-functions under this are:

   (a) **Storing energy**: Batteries are the best solution as they are reliable and provide long-term energy storage [HWK+21]. Hydrogen is not selected as it has a low energy density for storage and is inefficient in the conversion process.

   (b) **Converting energy in different ways**: A bidirectional DC-DC converter is chosen since it allows energy to flow in both directions, which enables efficient power transfer. AC-AC converters are not used since the majority of the devices are running on DC.

   (c) **Protecting circuits**: The battery protection circuit prevents over-discharging, short circuits, and excessive current draw, which ensures safe and efficient operations.

Function 2: The building is comfortable to live in.
This sub-function includes, as mentioned, air conditioning, utilities, safety, and social interactions. The means that are generated for this sub-function are weighted against the following criteria:

- **Sustainability:** The solution should have the least negative environmental impact. This means that CO2 emissions should be as low as possible and that energy waste should be kept to a minimum.
- **Feasibility:** The solution should be practical and implementable, which means it can be implemented within time without going over budget.
- **Comfortability:** The solution should include proper ventilation, lighting, temperature control, and reduced noise disturbance from the external environment.
- **Space:** The solution should take up minimal space in the constraints of the building.

Examples of means for the ventilation of the air in the house would be to open windows automatically, install mechanical ventilation, or place ventilation openings in the construction. The best mean for this sub-function is mechanical ventilation, as it is the most sustainable option. Ventilation openings come with a constant drought, whereas opening windows can waste energy. Mechanical ventilation can be turned on when needed, and the heat of the air can be stored or reused not to waste energy.

Function 3: The building is connected internally and externally. This sub-function focuses on the connectivity inside and outside the building and the flow of information. This is mainly important for controlling the systems of the building, keeping the building safe and secure, and for the residents to be able to communicate. The means are weighted against the following mean criteria:

- **Security**: The communication system must be able to withstand cyber attacks to keep privacy and prevent fraud.
- **Robustness**: The system must be able to operate under the influence of different environmental conditions and must always be able to make communication possible with the external world.
- **Speed of communication**: To have efficient transfer of information and communication, the speed of the signals must be high enough to make this possible.
- **Reliability**: The system must be functioning accordingly at all times without failure for safety and comfortability reasons.

Some examples of means for storing the system information inside the house are SSD, optical media (CD, DVD, Blu-ray), and hard disks. Only the first mean meets all the criteria. Hard disks and optical media are not as robust and reliable as SSDs.

6 Risk analysis

Up until this point, only the options that make the DC smart house a success were being investigated. However, it is a matter of utmost importance that the factors potentially leading to the failure of the project must also be taken into account for investigation before moving forward. This task was carried out with a risk analysis, where all the potential causes for hazards are listed together with the defined levels of impact of this event and its probability. The risks are divided into subgroups based on the phases of the project at which these can potentially occur:

- **Project development (PD)**: Risks that can occur in the project development phase, i.e. before the system is operational.
- **Operation (O)**: Risks that can occur under a system that is up and running.
- **Time independent risks (TIR)**: Risks that can occur during both the project development and operational phase.

The possible risks are listed under the right subgroup, and then it is decided what the impacts and probabilities are if and when a specific risk occurs. The different impacts and probabilities are given below:

Impact:

- **Catastrophic**: A risk that can lead to complete system failure, significant safety hazard or make the entire project non-viable.
- **Major**: A risk that causes major disruption to the system's functionality or leads to costly repairs and substantial loss of time.
- **Moderate**: A risk that causes a noticeable impact on the system and can be fixed with less cost and loss of time.
- **Low**: A risk that causes minimal impact on the system and only affects the non-critical components.
- **Negligible**: A risk that has almost no impact on the system and poses no real threat to the operation and safety of the system.

Probability:

Here, the period for the occurrence of an event has been defined into two sub-groups. Firstly, the probability of a risk happening during the project development stage is set for three years. Then, for the risks associated with the operational phase of the project, the observable time span goes about twenty years.

- **Almost certain**: 90% or higher probability of occurrence of an event in the defined time span.
- **Likely**: 60% to 90% probability of occurrence of an event in the defined time span.
- **Possible**: 30% to 60% probability of occurrence of an event in the defined time span.
- **Unlikely**: 10% to 30% probability of occurrence of an event in the defined time span.
- **Rare**: 10% or lower probability of occurrence of an event in the defined time span.

6.1 Risk Map

Upon listing numerous risks associated with the project into different subgroups (**PD, O** and **TIR**), the focus centers around determining the impact and probability of each risk separately. A comprehensive list of risks that may adversely affect the success of the project can be found in our Microsoft Teams channel.

This mapping technique helps in the categorical analysis of all the risks so that the ones that can pose a serious threat to the overall productivity of the project can be specifically listed. Upon identifying such unfavorable events, mitigation plans were implemented to reduce their impacts and occurrences.

Table 2: Risk Map

Risk Map					
Impact\Probability	**Almost Certain**	**Likely**	**Possible**	**Unlikely**	**Rare**
Catastrophic		TIR2	O15	PD2	PD4, PD13, TIR3, TIR7
Major		PD12, O10	O4, O8, O13	PD1, PD10, O20, TIR4, TIR6	PD7, O1, O2, TIR10
Moderate	TIR11	PD3, PD6, PD8, PD11, O14, O16, O19	TIR1	O11, O12	O5, TIR5, TIR9
Low	PD9, O3, O18, O21	TIR8	O7	PD5, O9	O6
Negligible			O17		

6.2 Bow-Tie diagram

A bow-tie diagram can be used to analyze a specific risk from the risk map. In the bow-tie diagram of Figure 5, the risk **O2: Electrical shocks**, which has an 'unlikely' probability and 'major' impact, is analyzed.

The hazard is listed in the center of the bow-tie, in this case, the increase in probability of accidents with electrical shocks. To the left of the center, the causes of this hazard are listed. These include an electrical overload and water infiltration in the wiring. To the right of the hazard, the possible events that can happen are shown. These include a fire due to short circuits and a failure of the internal power grid. To decrease the risk of electric shocks happening, the probability of the causes on the left should be minimized. This will be done by increasing the number of maintenance checks to reduce the probability of the top three causes and installing earth-leakage circuit breakers to decrease the probability of the bottom two risks, thereby reducing the probability of occurrence to 'rare'.

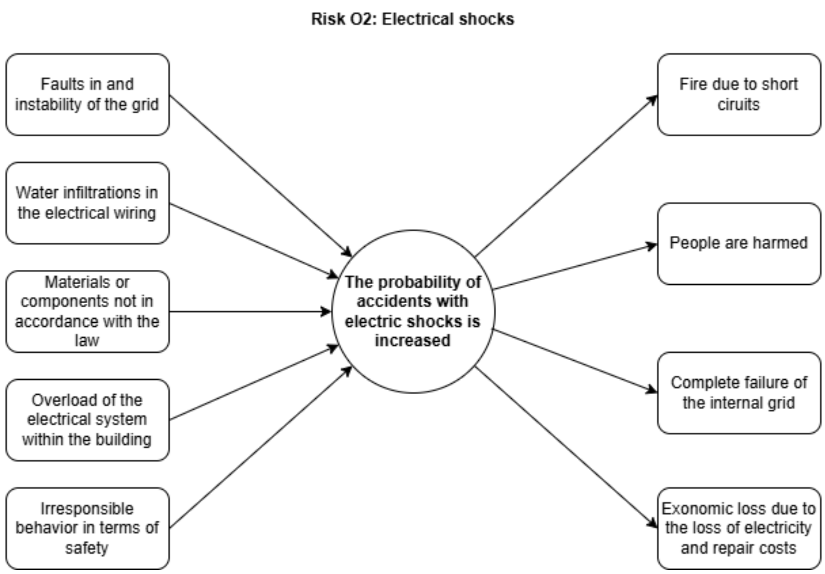


Figure 5: Bow-tie diagram for risk O2: Electrical shocks

6.3 Fishbone diagram

Another way of finding the causes of a risk is using a fishbone diagram. The risk **TIR4: Fire hazard in the building**, which has a 'major' impact and 'unlikely' probability, is considered the root cause in the fishbone diagram in Figure 6, which lists six primary causes: environment, methods, humans, materials, measurement, and machine.

Some examples from the fishbone diagram are that hazardous events can sometimes remain unnoticed due to inadequate measurements, such as an improper fire detection system and incorrect voltage and current regulation. Degraded machines like aging batteries or faulty converters also lead to system failures and potential fire. Summarizing, these factors collectively may cause a DC-circuit overload which eventually leads to fire hazards in the building.

Using the fishbone diagram, the possible causes of a fire hazard in a building were found. The mitigation plan that came up was to install fire detection and monitoring systems, use high-quality materials, and do regular inspections of the electrical wiring and electrical components. With this, the probability of the risk occurring was reduced from 'unlikely' to 'rare'.

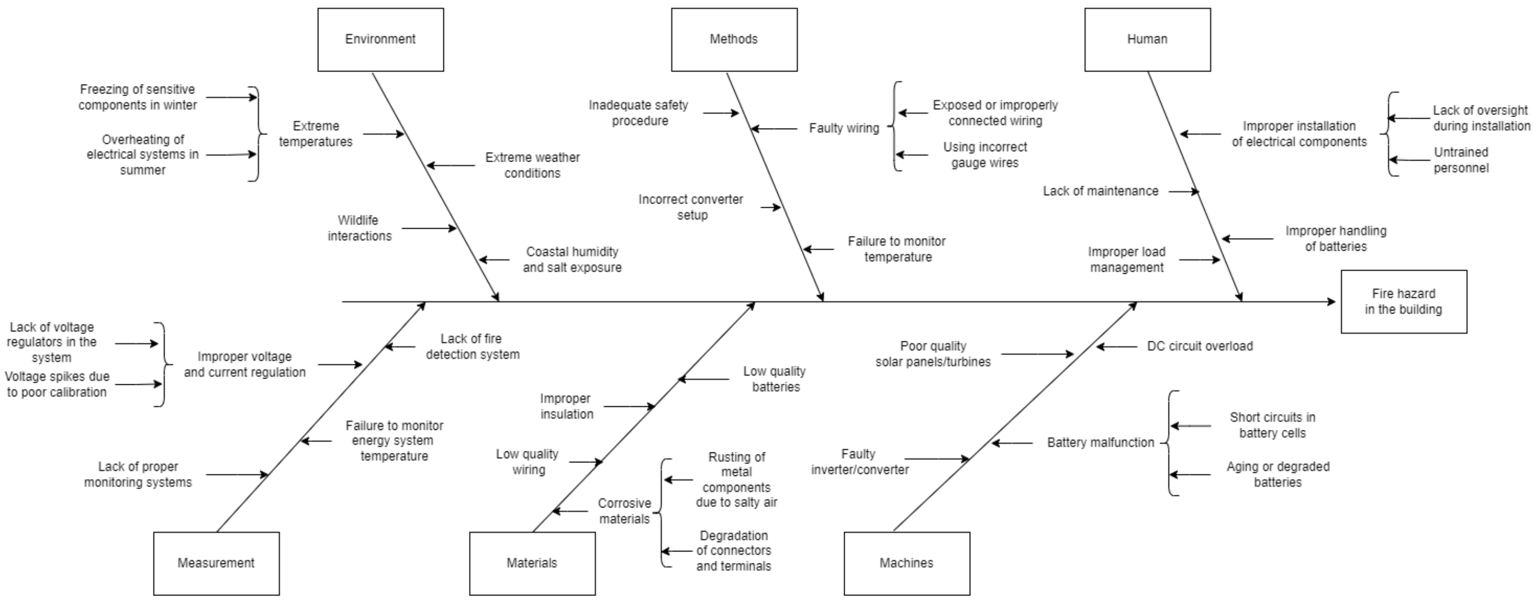


Figure 6: Fishbone diagram for risk TIR4: Fire hazard in the building

6.4 Mitigation plan

With the help of Figures 5 and 6, the root cause of the risks was identified. After finding the risks and characterizing them in the subdomains of impact and probability, the ones with catastrophic impact and almost certain probability must be mitigated and brought down to less impacting and less likely probability. An example procedure of risk mitigation is given below:

Risk O10: Changing weather conditions affects energy generation negatively

Impact and probability: Major and likely

Mitigation: Use a blend of energy sources, to be able to compensate for a lower production of another energy source. This supports the choice for having multiple different energy sources as in sub-function **1.1** shown in Figure 2

Impact and probability: Major and **Possible**.

The same procedure was adopted for all the high risks, and a corresponding mitigation plan was devised and implemented. The updated posterior risk map with all critical risks removed is given in the table below.

Table 3: Posterior Risk Map

Posterior Risk Map					
Impact\Probability	**Almost Certain**	**Likely**	**Possible**	**Unlikely**	**Rare**
Catastrophic				PD2	PD4, PD13, TIR3, TIR7
Major			O4, O8, O10, O13	PD1, PD10, O20, TIR4, TIR6	PD7, O1, O2, TIR10
Moderate		PD3, PD6, PD11, O14, O16, O19, TIR2, TIR11	TIR1	PD8, O11, O12	O5, TIR5, TIR9
Low	PD9, O3, O18, O21	TIR8	O7	PD5, O9	O6
Negligible			O17		

7 Simulation

To check for any unforeseen risks and to test the performance of a functional system, a simulation was conducted to observe whether the system is executing its functionalities in the desired manner for the success of the project.

7.1 Simulation plan

7.1.1 Overall system simulation plan

In the problem statement, it was stated that a blend of renewable energy sources must be implemented in the project to ensure enough and a stable supply of electricity for the residents of the building at all times. For this, a simulation should be done to find an optimal blend of different renewable energy sources. For this simulation plan, three different renewable energy sources are considered, which came out best in the morphological analysis in Section 5.1: mono-crystalline solar panels, (small) onshore wind turbines, and (small) tidal stream generators. These were found as the easiest possible electricity supplies on or near the designed building. To be able to store the energy, also a battery is included as a component of the system.

For the simulation purposes, the devised model was **dynamic** in nature as the amount of generated energy with various renewable energy sources kept on varying throughout the time span of twelve months with changes in wind speed, solar irradiance, and tidal wave profiles. In addition, a **deterministic** approach was taken into account for the project, as the predictable outputs can be fairly deduced using well-known components like peak load demand or battery storage capacity. The model will also be **continuous**, the state of the system at any time can be derived from the simulation. It will also be **non-linear**, the output does not have a linear dependency on the inputs of the model. For instance with the wind turbines in the model: the turbines only deliver energy in between certain wind speeds. When the wind speed is too low, the turbines will stand still. When the wind speed gets too high, they will shut down for safety reasons.

For a simulation plan also the available data inputs should be mentioned. This data should at all times be correct to perform a good simulation.

- **Electricity generation:** Electricity generation is influenced by the wind speed (m/s), solar irradiation (W/m^2), and tidal wave power (kW/m).
- **Batteries:** Current battery charge (kWh), to track the ability of the battery to store or release energy to the system.
- **Electricity use:** The average household power use in Perth, Australia ($kWh/month$), to see if enough energy is produced and stored.
- **Time keeping:** The current time (hr) since simulation start.
- **Selling of electricity:** Current electricity price (AUD/kWh), to see if it is economical to sell electricity at the given time.
- **Available space:** The space (m^2) available on the roof and the land plot for the placing of possible electricity generation options.

After the available inputs are set, some assumptions have to be made. This is done to make sure that the simulation will stay bounded and will not become too complex to perform. A good example from the simulation plan is that all the equipment is installed and functioning properly during the simulation. This is included to make sure that the simulation does not have to include any chances of malfunctioning equipment, which would make the simulation more complex. Other assumptions can be found in the full simulation plan in our Microsoft Teams channel.

Next, the initial conditions for the simulation have to be set. These initial conditions create a starting point for the simulation, that needs to be chosen as close as possible to the real world situation. For this project, this will be the day that the apartments are delivered to the residents. This results in the following initial conditions: The batteries start empty, there is no power demand, the starting time is equal to 00:00 (which corresponds to 12:00 during the day) and the temperature will be 25 degrees Celsius, the average temperature in Perth in summer.

With all of these parts implemented in the simulation plan, it should generate output for the optimal blend of energy production methods to harvest as much energy as possible with the available space.

Lastly, Python [VRDJ95] is chosen as software for performing the simulation, due to its simplicity and extensive libraries, which will speed up the coding of the simulation.

7.1.2 Component simulation plan

For the simulation of the entire project, it will be very useful to know the behavior of the solar panels under different circumstances such as more cloudy weather, lower temperatures, different angles to the sun, or different voltage levels. To analyze how a solar panel behaves under different circumstances, a **static, linear, deterministic, and continuous** model of a solar panel will be made. For now, due to its simplicity and the extensive explanation of the full system simulation plan, it will not be further explained. The simulation plan for the component can be found in our Microsoft Teams channel.

7.2 Performed simulation

This simulation focused on deciding the best combination of renewable energy sources, in order to power the whole building.

Firstly, the average monthly power consumption of an apartment over an entire year in Australia was collected[RPD+12] and an "additional energy of 2000 kWHrs" [oA] for facilitating power supply across EV parking charging points was also taken in consideration. This "additional energy" is then divided by 12 and summed with the average monthly power consumption values of one household. At last, multiplying the sum value by 60 (the number of apartments in the building) for each month will fetch the results for average power consumption trends for the entire building. After that, the choice was made to not display the output from tidal stream power plants in Figure 8, because it was completely out of scale in terms of energy production if compared with the other energy sources. Moreover, using a dynamic tidal power plant would make the simulation too complex. In order to have an overall understanding of the system performance in terms of kWh, energy produced during 12 months is taken. The models used for the solar panels and wind turbines are:

- pvlib [AHH+23] is used, to model a solar panel with the following parameters: 250 Watt nominal power and a temperature coefficient of -0.004%/°C.
- Enercon E18 [Bau] wind turbine (height = 35 meters) used in windpowerlib [HKS+24] in Python.

Once all the trends were plotted, a comparison was visually performed, choosing a combination that was fully able to cover the yearly energy demand in terms of consumption, shown in 8. After the selection, the data computed and obtained through the simulation are returned to the user in the form of the number of total energy generated, cost of the chosen combination (solar + wind) and battery capacity needed.
A more detailed workflow of the simulation can be found in Figure 7.

7.3 Simulation code

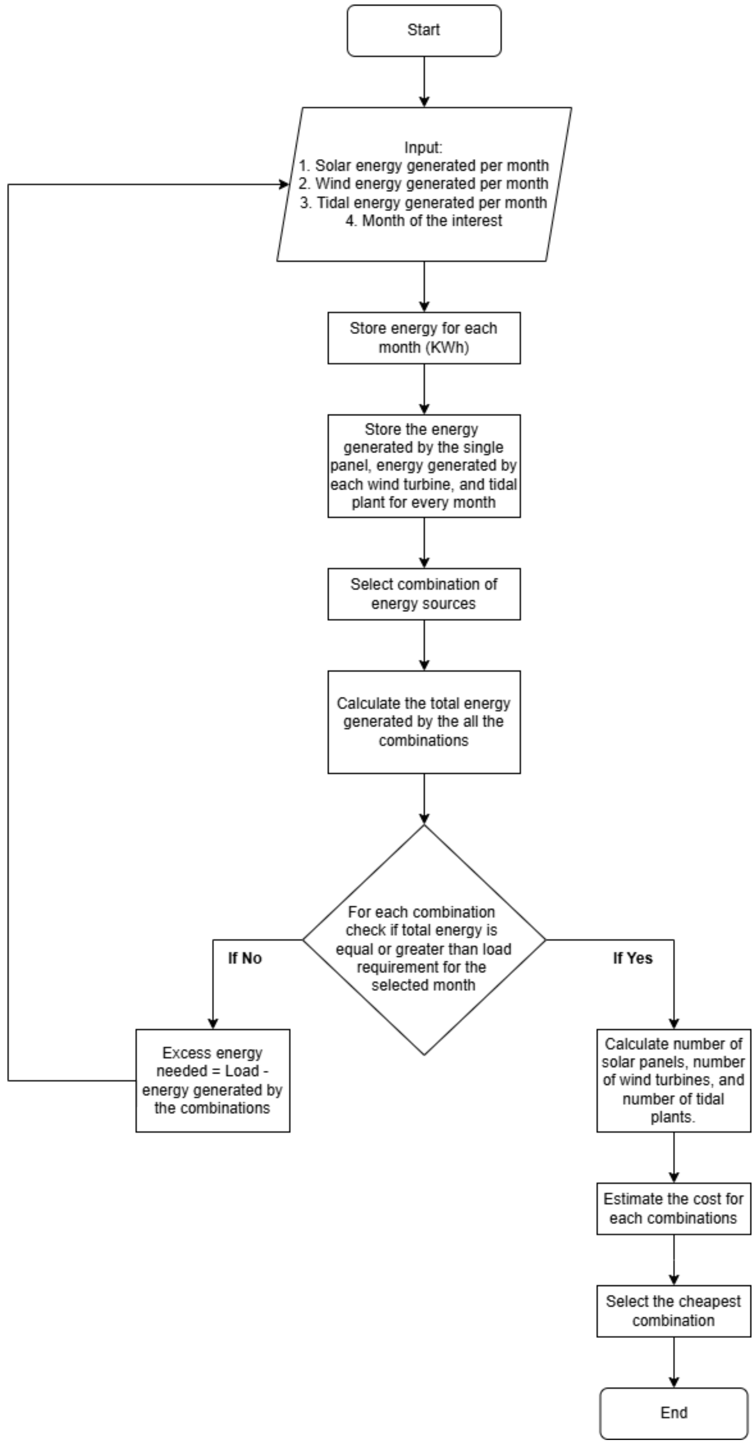


Figure 7: Flowchart of the implemented simulation plan

The aim is to find the best possible set of available renewable resources that demand lower investments in exchange for energy provision. The flowchart follows the steps described below:

1. Initialization: The user enters the following data:

(a) Estimated solar energy production for a given month.

(b) Estimated wind energy production for a given month.

(c) Estimated tidal energy production for a given month.

(d) The month(s) in question regarding the needed energy.

2. Monthly energy data storage [RPD+12]:

(a) The amount of electricity produced from solar, wind, and tidal resources for every individual month is extracted from the models of solar, wind, and tidal for each month of the year based on the conditions of Perth, Australia.

(b) The total energy output per solar panel, wind turbine, and tidal plant is recorded.

3. Energy combinations: Possible combinations of energy types have been identified, that is solar+wind, wind+tidal, and solar+tidal.

4. Total energy values: The total energy generated by each viable combination of resources is determined.

5. Energy requirement:

(a) Each viable combination's output energy is tested against that month's load requirement.

(b) **If the energy produced is less than the energy required:**

- The system counts the deficiency and checks again for additional energy production to meet the load.
- The load will be rechecked at the next level.

(c) **If the energy output is equal to or greater than the required load:**

- The number of solar panel arrays, wind turbines, and tidal plants needed is calculated.
- The cost of each combination is estimated.

6. End: The cheapest energy combination that meets the energy requirement is selected.

7.4 Simulation Output

The table below summarizes the results of the simulation. The simulation was run with inputs taken from the user for the rough monthly energy generated from solar, wind, and tidal sources. The user is also prompted to enter the month of interest, which selects the load requirement of the apartment for calculation. From the simulation result, it can be inferred that the 'solar + wind' combination is the [cho24] [Ink24] and the most feasible option with 100 solar panels and 2 wind turbines, which meet the energy requirement of the house as well as produce excess energy that can be sold to the grid. The tidal plant was discarded due to its high setup cost and high energy production, which is significantly higher than the requirement.

Table 4: Simulation Output Showing Different Energy Combinations and its Cost

Combination	Total Energy Generated (kWh)	Energy Requirement Met	Total Cost (AUD)	Solar Panels	Wind Turbines	Tidal Plants
Solar + Wind	665000	Yes	57700	100	2	0
Wind + Tidal	780125000	Yes	2520000	0	2	1
Solar + Tidal	780540000	Yes	2517700	100	0	1

The results from Table 4 can be verified visually from Figure 8, which shows the energy generation and household load for each month throughout the year. Wind energy alone will also produce enough energy throughout the year, but to mitigate the risk **O10: Changing weather conditions affects energy generation negatively**, solar energy should also be considered. For this reason, the complementary combination of solar and wind is fixed as the final solution.

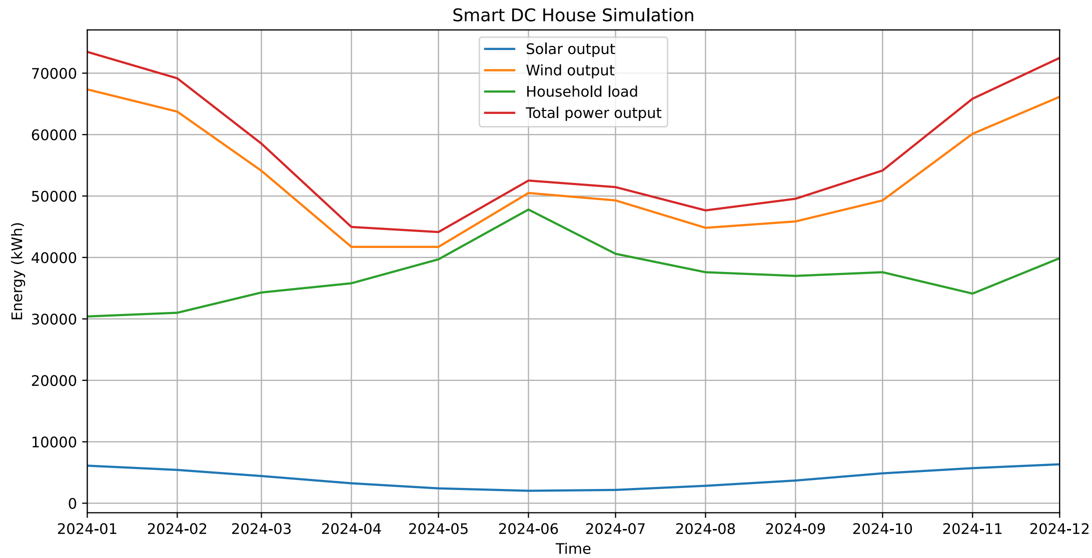


Figure 8: Input and output energy of the system with 100 solar panels and 2 wind turbines

8 Testing

After construction is finished, the system must be tested to ensure the system is in accordance with the requirements (Section 4) and whether all requirements are met. Therefore, elaborate testing plans at both component level and system level must be created.

The high-level function being tested from function 1 of the functional decomposition (Section 5), is whether the power supply stays below the required 400 V during operation, or is less than 0.5 seconds higher than this value. Consecutive over-voltages are not allowed within a 1-second time frame.

If the voltage is higher than 400 V for a certain time period, the system or the appliances could be damaged. In the worst case, a fire can be caused through over-voltage. The condition for this test is that the voltmeter has been calibrated. Also, at the start of the experiment, the voltage of the energy system within the apartment must be 0 V. The voltage is monitored continuously at a central point in the energy system. During normal operation, every minute the voltage level will be logged. If over-voltage occurs, each 0.1 s a measurement will be stored in a separate log, such that the behavior of the over-voltage can be thoroughly analyzed. This continuous measuring and monitoring of the voltage makes it possible to make an adequate log of whether the voltage surpasses 400 V throughout the testing.

The low-level function being tested is the HVAC (heating, ventilation, and air-conditioning) system which can be found as function 2.1 in the functional decomposition in Section 5. Without a properly functioning HVAC system, the temperature within the apartment can become inhuman. The related requirement stated that the HVAC system must be able to regulate and maintain the temperature between 20 and 26°C [SCMOAG21]. An important assumption is that the doors and windows between the apartment and the external environment are closed. A condition for testing the HVAC system is that if the HVAC system is turned on, any other heating or cooling sources must be turned off. The temperature will be measured continuously. However, once every 10 minutes the temperature will be logged if the temperature is within the set bounds of 20 to 26°C. If, during the continuous measuring of the temperature, the temperature is out of these bounds, then the temperature will be logged every minute. The test consists of two parts, for the first part heaters will be used to increase the temperature to 33°C. For the second part, air-conditioners will be used to decrease the temperature to 12°C. The temperature will be increased or decreased to these temperatures before the start of the actual test. If the 34°C for the first experiment or 12°C for the second experiment is reached then all the heaters or air-conditioners are turned off. Simultaneously the HVAC system will be turned on. The HVAC system must be able to bring the temperature between 20 and 26°C within 30 minutes. After the HVAC system successfully brings the temperature back within the set bounds, it is tested whether the HVAC is able to maintain the temperature between the set bounds for a time duration of 24 hours.

The full testing plans can be found in our Microsoft Teams channel.

9 Conclusion

Through systematic evaluation of the project statement, building a self-sustaining, DC-powered, and financially viable neighborhood of apartment buildings in Perth, Australia, is feasible when the right design measures are taken. These apartment buildings are powered by complementary renewable energy sources of solar and wind, without consuming energy from the electricity grid.

Teamwork

At the beginning of the project, the thought process with which the problem statement was approached set the platform for developing insightful ideas and meeting a common point of convergence. Through brainstorming sessions, multiple ideas were put together, and a blend of complementary solutions was chosen to fit into the scope of the project. Executing this task proved to be the first hurdle that the team encountered during the inception phase but collectively working on the feedback received from the mentors helped in steering the project in the right direction.

In the realization of the SDM, some vision discrepancies were still present and only after finishing it, we started to have a more shared common vision of a possible solution to the problem statement. In the middle of the project, we looked back at the first half of the project. There were some disagreements and major miscommunications about the meetings and the teamwork. These were expressed and we made new agreements. These agreements are that we want to work more efficiently during the group meetings and that we clearly state what we are going to do or have done before and after a group meeting.

The second half of the project consisted of a process of deconstruction for the results obtained so far and each member was able to implement their ideas more practically. At this point, we focused on working more efficiently by distributing the tasks into sub-groups where everyone communicated their ideas with a clear vision. As each team member was well aware of the assigned workload, tedious tasks of the project were given great attention to detail and complete the tasks within the expected timeline. For the testing phase, the entire team decided to check the performance of the system to find the most financially viable blend of renewable sources for DC power generation in the building. This shows the commitment level of the team to keep hustling for the optimal solutions that can be feasibly modeled to build DC smart home.

In the end, we can say that we worked well together as a team, and all problems encountered during the journey from our perspective were solved. If we should start the project from scratch, we should discuss the expectations from each other in more detail at the start. Regarding the future work to be done, it would be possible to move on to the practical implementation of the project.

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