University of Toronto
Faculty of Applied Science and Engineering
APS112 & APS113
Conceptual Design Specification (CDS)

Project #	57	Date	Monday, February 29, 2016

Project Title	Solar Cold Cellar in Kalahari Desert	
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- ✔ Cover Page
- ✔ Executive Summary
- ✔ Project Requirements
- ✔ Alternative Designs
- ✔ Proposed Conceptual Design
- ✔ Updated Project Management Plan
- ✔ Conclusion
- ✔ Reference List
- ✔ Appendices

✔ Turnitin Submission

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Executive Summary

The client Ms. Joanne Hutchinson, president and founder of the charity Socio Economic and Environmental Development Solutions (SEEDS), has expressed a desire for a single cellar for use in Mongu, Zambia. The cellar is meant to preserve food for local farmers during the 5 month long dry season in order to alleviate the effects of seasonal food shortages and lack of food diversity. The design will control storage temperature and humidity in order to preserve food.

The stakeholders include several bodies from the zambian government, several NPOs and local farmers. These include such bodies as the Ministry of Lands, the World Food Programme and the Zambia National Farmers Union. The service environment of the design includes sandy, dry terrain with high temperature and low humidity during the dry season, and high humidity during the rainy season. These combined with the design's gap, and the client's ethics and values were analysed and used to determine the functions, objective, and constraints, notably keeping the temperature below 10 degrees celsius.

Several strategies including structured brainstorming and a morphological chart were used to create a list of 46 possible designs. These designs were then checked to ensure that they satisfied the functions, with any failing designs being removed. Multi-voting and consensus was then used to reduce the list down to the 5 conceptual designs; The Hillside Evaporative Cooling Cellar , the Night Breeze Cooling Cellar, the Reflective Wind Tower Storage System, the Underground Compression System, and the PCM Layered Storage System.

The 5 remaining designs were compared using a weighted decision matrix in order to find the design with the best compromises. The team chose the Underground Compression System (UCS) as the suggested design as it had the most optimal balance of objectives being met. The design uses compressed refrigerant to cool down the cellar and is placed underground for additional insulation. It exceeds the first objective to maintain temperature, while having small compromise due to higher costs. It also meets the remaining objectives of durability, environmental sustainability, grid independence, security and storage capacity, while respecting the constraints.

Based on the proposed design, economic and environmental life cycle assessments, social impacts, human factors, outstanding design decisions and preliminary design requirements were outlined. Following the client's decision, the final design specifications will be prepared where more details will be provided, and changes may be made based on outstanding decisions, and will be presented to the client at a later date.

1.0 Project Requirements

This document outlines the client, Ms. Joanne Hutchinson's project on developing a food cellar in Mongu, Zambia[1]. Ms. Hutchinson is the founder of the Canadian registered charity SEEDS. Her diversified interests include social and environmental initiatives.

1.1. Problem Statement

With 48% of its population below minimum dietary energy consumption in 2013[2][3], undernourishment in Zambia results from seasonal food shortage and lack of food diversity[4][5]. Seasonal changes in climate and chronic droughts[6][7] lead to declines in crop yield during the dry season--from May to September [7][8]. The client wants to build one food cellar to preserve produce and canned goods for farmers in Mongu to alleviate food shortage and malnourishment[1]. Currently, refrigeration systems are used to extend shelf-life and preserve food integrity[10][11]. Such systems are expensive—costing over $6,000, and are unaffordable to local farmers making $1680/year [2] as well as charities like SEEDS [11][12]. There lacks an economically viable food preservation system targeted for use in Zambia.

The client needs an inexpensive system, costing less than current alternatives, that controls relative humidity[11], pathogens[13] and storage temperature[10] to store and preserve produce and canned foods for short periods of time[1], primarily during the 5 months dry season. Control of these factors extends produce shelf life [9][10][13]. Finally, it must abide by the client's ethical concerns and values, have minimal environmental impact and ensure the operator's' safety [1].

1.2. Identification of Stakeholders

The design of a new food cellar for SEEDS, for use by farmers in Mongu, will require the consideration of stakeholder's goals and interests. Stakeholders include organisations from the governmental and private sectors, each having varying impacts on objectives and constraints. The stakeholders for this project are Zambian governmental bodies, NPOs and local farmers.

Table 1. Stakeholders and Their Interests and Impact on the Design Project

Stakeholder (Descending influence)	Interests	Impact
Zambian government ● Ministry of Lands ● Environmental Council ● Mongu Municipal Authority	● Public welfare, safety, and health [14]	● Constraint: Design must be safe, and adhere to construction standards
Analogous NPOs (Non-profit organisations) ● Tikondane.org ● World Food Programme	● Provide seeds/food to impoverished regions [15] ● Reduce poverty in Zambia[16]	● Objective: Design should be inexpensive
Local Farmers ● Zambia National Farmers' Union ● Mongu District Farmers Association(MDFA)	● Extend shelf-life of fresh produce[17] ● Maintain soil fertility[18] ● Improve food production[19]	● Constraint: Design must not damage environment [1] ● Objective: Design should be inexpensive ● Objective: Design should have minimal environmental impact

1.3. Functions

Food preservation is achieved by controlling relative humidity and storage temperature. The functions below define the necessary parameters for the cellar design to meet the client's needs.

They are generated using the black box method[Appendix A].

1.3.1. Functional Basis

- The functional basis is to maintain mass and energy

1.3.2. Primary Function

- Preserve fresh produce and canned goods by controlling temperature
- Preserve fresh produce and canned goods by controlling moisture

1.3.3. Secondary Functions

- Contain produce and canned goods
- Protect food from local weather
- Allow produce and canned goods to be inserted and extracted
- Prevent unwanted beings from consuming the stored food

1.3.4. Unintended Functions

- Store seeds and equipment
- Act as shelter for locals and animals

1.4. Objectives

Objectives help evaluate the success of a design. They outline goals to be achieved based on the client's requirements, needs, and values [24]. Pairwise comparison is used to rank the objectives and assign relative weights[Appendix B]. The client's needs are addressed in objectives 1 and 2, in which the cellar aims to preserve produce during the 5-months-long dry season while minimizing cost.

Table 2. Design Objectives and Goals

Objectives (Descending Importance)	Goals
1. The design should preserve food for 5 months	• Maintain temperature between 0 and 10°C [20] • Maintain relative humidity between 80 and 90% [20][21]
2. The design should be inexpensive	• Price half that of congeneric food cellars, and thus less than $3,000 [12][22][23]
3. The design should have minimal environmental impact	• Use recyclable materials [24][25]

4. The design should be durable	• Withstand precipitation, withstand external temperatures (52°C)[26] • Resist oxidation, corrosion, change of shape [27][28] • Resistant to termites, ants [29]
5. The design should be secure	• Have two barriers to entry [30][31][32]
6. The design should not be reliant on external electricity [1]	• Minimal reliance on external electricity due to availability [1]
7. The design should hold different types of produce	• Contain at least 3 types of produce [1] • Height: 1.5-2.0 m [1][33] • Storage capacity 5.0-15m^3 [1][34][35]

1.5. Constraints

Constraints are absolute limits that designs must abide by. They arise from Zambian government regulations and laws, and client ethics and values.

1.5.1 For the design to be built in Mongu, it shall [36]:

- Obtain property title from the Ministry of Lands
  - Follow Lands and Deeds Registry Act [37]
- Obtain approval from the Environmental Council
  - Follow Environmental Management Act [38]
- Be permitted by Municipal Authority

1.5.2 For the design to be considered by client, it shall:

- Follow ISO food storage standards (ISO-22000:2005) [39]
- Not contain loose or hazardous materials
- Not contaminate its contents

1.5.3 The design shall[1]:

- Occupy no more than 9.2m^2 surface area
- Not harm operators' health
- Not create disruptive amounts of light or noise
- Not affect surrounding wildlife

1.6. Service Environment

The cellar will be built in rural Mongu, Zambia [1][40]. Thus, analysis of service environment focuses on Mongu to examine the external conditions—living things, physical and virtual environment—affecting and affected by the design.

Table 3. Physical Environment, Living Things, and Virtual Environment

1.6.1 Physical Environment	
Climate [1][41][42][43]	● Dry Season(May-September) ○ precipitation: 0-50mm/month ○ temperature: 9-27°C ○ relative humidity: 35-60% ● Rainy season(October-March) ○ precipitation: 416mm/months ○ temperature: 18°C-34°C ○ relative humidity: 42-84%
Sunlight	● daytime average intensity: 0.5kW/m^2 [42][43] ● duration: 180-300 hours/months [44]
Wind	● average speed: 3-8m/s [42][43]
Land	● composition: Sandy and infertile[45] ● affected by erosion, desertification [46] ● highly fertile plains experience chronic drought or flooding [47][48][49]
Inside food cellar	● temperature: 0-10°C [20] ● relative humidity: 80-95% [21][20]
Transportation[1][41]	● majority of roads passable by four-wheel vehicles ● airplane: Mongu Airport
1.6.2. Living Things	
Microbes and bacteria	● *e. coli* exists in small concentrations in the local water supply [50]
Insects and animals	● fish, eagle, woodpeckers [51] ● termites/white ants can damage buildings [52][53]

Food cellar operator	• farmers with expected grade 8 education [54] • average male height: 1.67m [55] • average female height: 1.59m [33][56]

1.7. Client Ethics and Values

Ms. Joanne Hutchinson is the founder of SEEDS, a Canadian registered charity that supplies seeds to Zambian farmers for financial assistance[40]. Valuing charitable causes, Ms. Hutchinson's efforts include sponsoring a Zambian child's education, and providing seeds to impoverished areas like Barotseland [40]. She also values environmental conservation in Africa and protection of endangered species such as the African elephant in Zambia [57].

2.0. Alternative Designs

This section details five food cellar designs; all designs fulfill primary and secondary functions, and abide by constraints. The team used structured brainstorming and a morphological chart to generate 46 design ideas. Designs that failed to satisfy functions and constraints are discarded. Multi-voting yielded 7 high-scoring design, which are evaluated on its ability to cool storage temperature and its environmental impact. The final 5 alternative designs are decided using consensus.

Appendices C, D detail the idea generation and selection processes.

Appendix E specifies objective evaluation criteria.

2.1. Hillside Evaporative Cooling Cellar (HECC)

This design is buried 1m underground into a hill on the site [1][[Figure 1]. Powered by a 30 Watt solar panel, the design uses the ground's thermal capacity to cool an air current passing through the naylor pipe. A fan blows the air through a perforated foam cylinder drenched in water. The water then evaporates, thus cooling the air [58] which is then channeled into the cellar, maintaining low temperatures and high humidity[Appendix F].

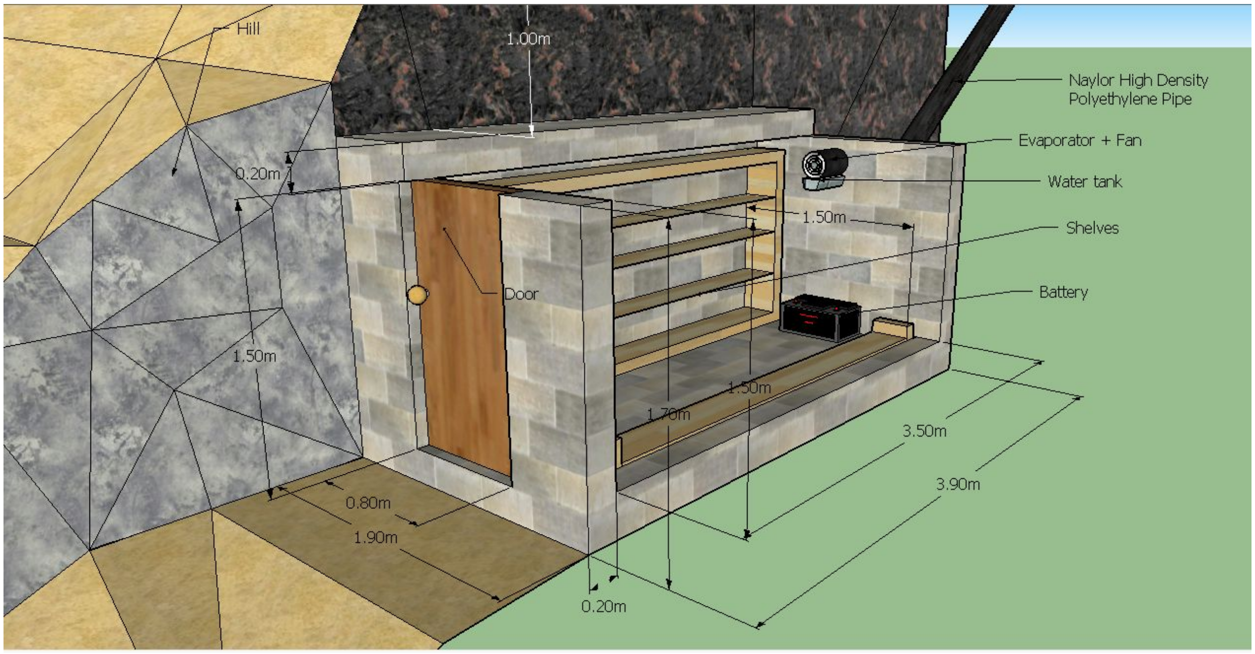

Figure 1. Hillside Evaporative Cooling Cellar Schematic

Table 4. Objective Evaluation of Hillside Evaporative Cooling Cellar

Objective	Description ✓ advantage ▫ disadvantage	Percentage Met (%)
O1.	✓ Maintains temperature below 10°C [Appendix F] ▫ Humidity kept near 100%, (ideal 80-90%) [Appendix F] ▫ Less effective during humid seasons [59]	70
O2.	✓ Material cost: $950 [Appendix F]	100
O3.	✓ Concrete is recyclable[60] ✓ High-density-polyethylene recyclable[61]	90
O4.	✓ Concrete is water, weathering, chemical attack and abrasion resistant[62] ✓ Concrete walls support 4.6 MPa (max 42 MPa) [Appendix F] ✓ Concrete resistant to pests[63]	100
O5.	✓ Key lock on entry door	90

O6.	✓ Powered by 30W solar panel	100
O7.	✓ Storage capacity: 6.2m^3[Appendix F]	100

2.2. Night Breeze Cooling Cellar (NBCC)

The design, half submerged under ground[Figure 2], is built with Portland cement plaster. Closed cell spray foam insulation is applied on the interior walls to lock in moisture[64]. The cellar incorporates a NightBreeze system to control temperature through circulation of cooler nighttime air to remove the heat in the cellar's thermal mass during the day[65].

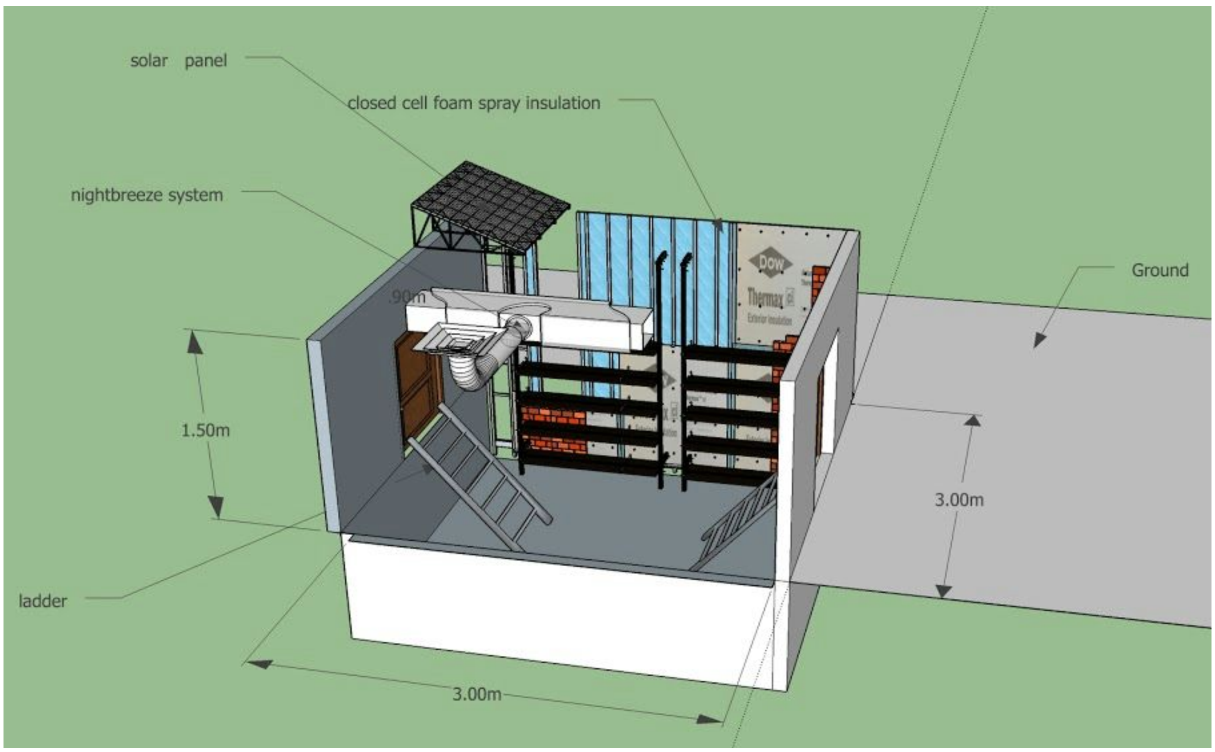

Figure 2. Night Breeze Cooling Cellar

Table 5. Objectives Evaluation for Spray Foam Cooling System

Objective	Description ✓advantage ▫ disadvantage	Percentage Met (%)
O1.	✓ Closed cell spray foam is maintains humidity[64] ✓ Nightbreeze system removes heat from the	70

	cellar[65] ◻ Cooling extent dependent on nighttime temperature[65]	
O2.	✓ Material cost: $2,850 [Appendix G] ◻ Transportation cost for NightBreeze system	80
O3.	✓ Portland cement is 100% recyclable [67] ◻ Few Portland cement recycling sites[68]	90
O4.	✓ Portland cement plaster is waterproof/ resists chemical attack[69]	95
O5.	✓ Double cylinder handleset with knob for both barriers	80
O6.	✓ Power provided by solar panels	100
O7.	✓ Storage capacity: 12.0m^3[Appendix G] ◻ Staircase occupies storage volume	80

2.3. Reflective Wind Tower Storage System (RWTSS)

The RWTSS consists of a concrete geodesic dome structure above ground and a cylindrical structure underground[Figures 3,4]. Two wind towers direct air currents into the cellar to cool it down , reducing storage temperature by 23%[70][Appendix H]. The cellar also uses heat reflective materials on its exterior to reflects over 83% of incoming heat[71].

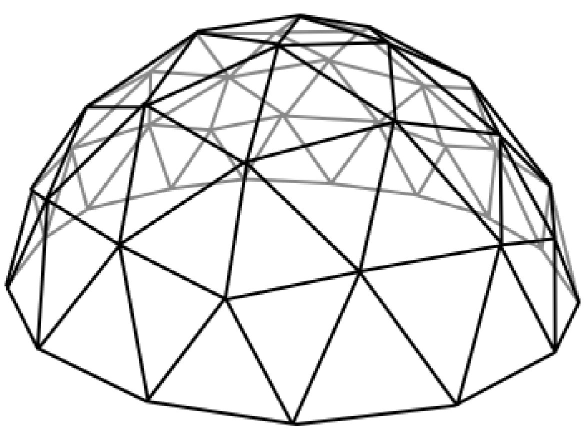

Figure 3. Structural Depiction of Above-ground Geodesic Dome[72]

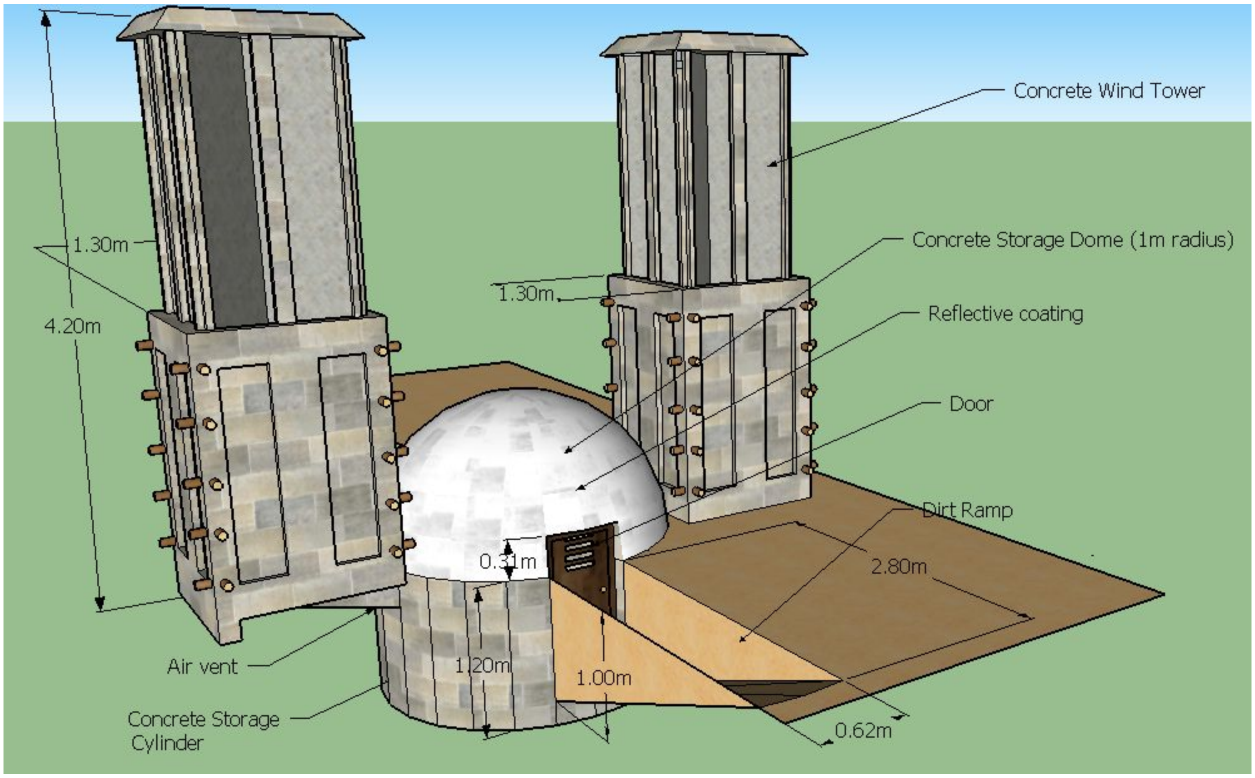

Figure 4. Reflective Wind Tower Storage Schematic

Figure 5. Cellar Interior Depiction

Table 6. Objectives Evaluation for Reflective Wind Tower Storage System

Objective	Description ✓ advantage ▫ disadvantage	Percentage Met (%)
O1.	✓ Reflective materials reflect 83% of thermal radiation [71] ▫ Humidity identical to exterior humidity ▫ Wind tower only cools temperature by 23% [Appendix H]	65
O2.	✓ Material cost: $2,174	85
O3.	✓ Concrete recyclable [60]	95
O4.	✓ Concrete withstands pressure:20-25 Mpa[E], resists weathering, chemical attack [62] ✓ Concrete resistant to pests [63] ✓ Geodesic dome has highest weight-volume ratio-structurally strong [73]	100
O5.	✓ Entry door secured by a lock	90
O6.	✓ Passive cooling system requires no electricity	100
O7.	▫ Storage capacity: 5.23 m^3 [Appendix H]	70

2.4. Underground Compression System (UCS)

The UCS, situated 2.4 meters below ground[Figure 6], uses the cooler temperatures of the ground to insulate and cool the cellar. The design uses a 2-horsepower compressor to condense a refrigerant within a copper coil, which absorbs the heat in the cellar [73]. This heat is then expelled into the surrounding ground, resulting in storage temperatures as low as -10°C.

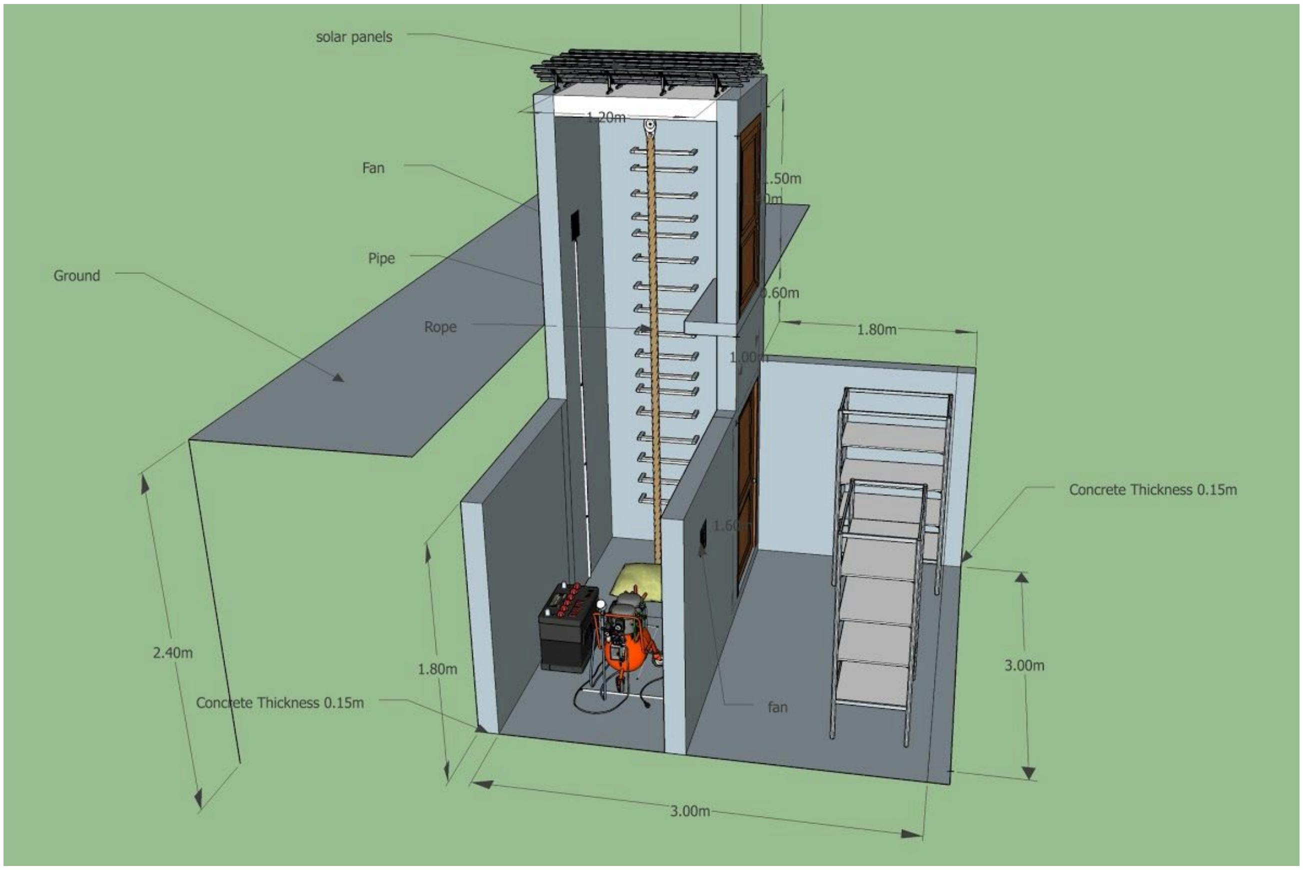

Figure 6. UCS Schematic

Table 7. Objectives Evaluation for UCS

Objective	Description ✓advantage ◻ disadvantage	Percentage Met (%)
O1.	✓ 2-horsepower compressor can cool temperature to 0°C [74] ✓ Average ambient soil temperature: 16.2°C [75] ✓ small humidifier increases humidity.	100
O2.	✓ Materials cost: $2,052 [Appendix I]	90
O3.	✓ Concrete recyclable [60] ✓ Closed compressor loop prevents refrigerant leaks ◻ Ozone depletion and global warming from refrigerant disposal[76] ✓ Copper tubing recyclable [77]	90

O4.	✓ Concrete, pests-resistant, resists weathering[62][63] ✓ Concrete walls support 5.85 MPa (max 42 MPa)[Appendix I] ✓ Door seals increase water resistance	100
O5.	✓ Single cylinder deadbolt secures entrance door	90
O6.	✓ Two 500 watt solar panels(13.1° tilt)[85]	100
O7.	✓ Storage capacity: $5m^3$ [Appendix I] ▫ Above ground space not utilised	70

2.5. PCM Layered Storage System (PCMLSS)

The design, situated above ground[Figure 7], incorporates a layer of phase change materials(PCM) between an external concrete layer and interior moisture-resistant plasterboard[Figure 8]. The design uses latent heat properties of engineered PCMs during phase change, and reflective roof coatings to keep storage temperatures within a specific range[78]. Eco-friendly humidifiers[79] are used to control humidity, achieving produce preservation.

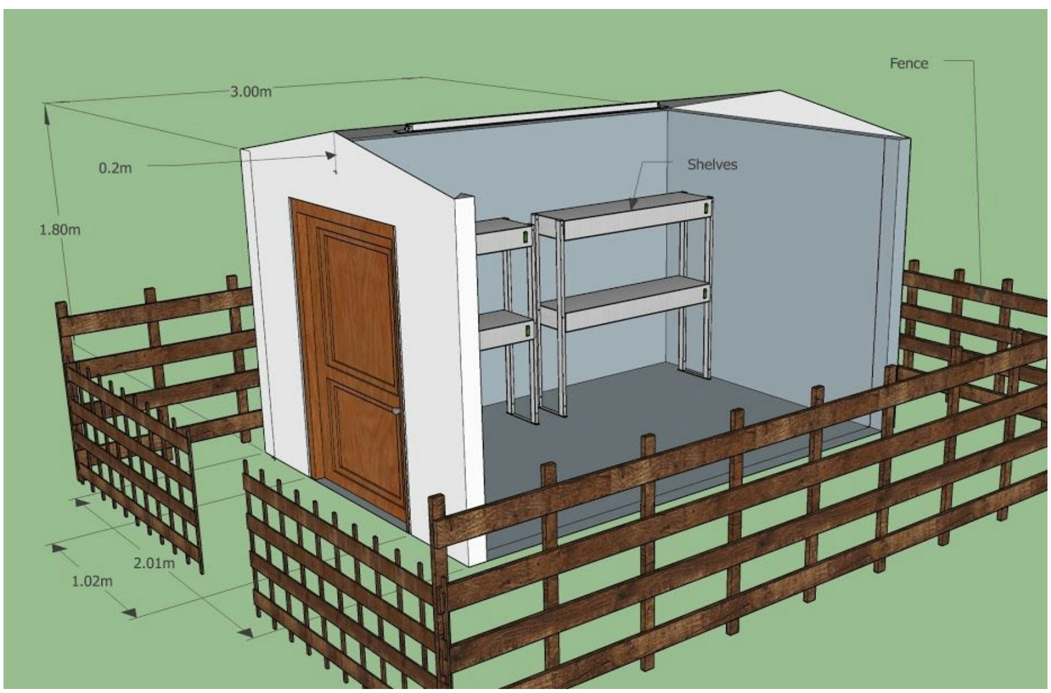

Figure 7. Above-ground PCM Layered Storage System

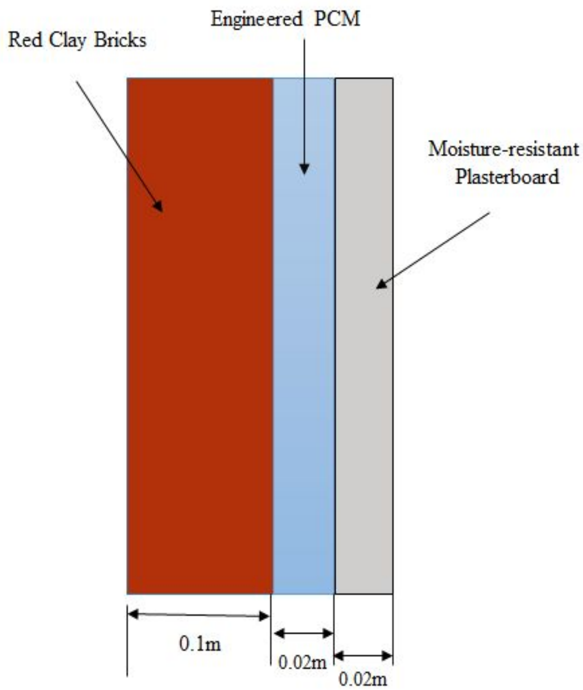

Figure 8. Top-Down-View of Wall Composition

Table 8. Objectives Evaluation for PCM Layered Storage System

Objective	Description ✓ advantage ▫ disadvantage	Percentage Met (%)
O1	✓ Engineered PCM can match storage temperature requirement [78] ✓ Reflective roof coating reduces heat transfer [80] ✓ Humidifiers increase humidity [79] ✓ Clay bricks provide insulation [81] ▫ PCMs release heat when temperature drops below melting point [82]	70
O2.	✓ Material cost: $3,115 [Appendix J] ▫ Extra cost to develop PCM for 0-10°C storage [83] ▫ Export cost for PCM	65
O3.	✓ Recyclable clay bricks [81] ✓ PCM biodegradable [78] ▫ PCM disposal requires incineration[83]	80

O4.	✓ Rhombic-shaped roof prevents rainfall accumulation ✓ Clay bricks resistant to pests [84] ✓ Reflective coating extends life of roof [80]	90
O5.	✓ Locked wooden door ✓ Fenced off	100
O6.	✓ Humidifier re-uses existing air flow--no electricity required [79]	100
O7.	✓ Storage capacity: 7.2 m^3 [Appendix J] ✓ Height 2.0m, occupies ground area 6m^2	95

3.0. Proposed Conceptual Design

In fulfilling the objectives, a compromise exists between the design's ability to preserve produce and its cost. Evaluation of the 5 alternative designs with a weighted decision matrix [Appendix K] shows that the optimal balance between functionality and cost is achieved by Design 2.4. Underground Compression System (UCS). The design is isolated from the warm ambient air temperature. The use of a 2-horsepower compressor, complemented by optimal cooling effects from surrounding soil in the UCS allows for extra stability and consistency in maintaining storage temperature--a feature lacking in other designs.

3.1. Proposed Design - UCS

The Underground Compression System(UCS) is a large, two roomed concrete cellar, measuring 3mx3m with height of 1.8m. It sits 0.6m below ground with the floor 2.4m below ground[Figure 9]. The design makes use of the lower average temperature of the ground of 16.2°C[75] as well as a 2-horsepower compressor and a small humidifier, both powered by two 500 watt solar panels, to keep interior cellar temperature at around 0°C[74][Figure 10]. The compressor takes advantage of the the thermochemical properties of liquids and gases by evaporating and condensing a refrigerant within a copper coil. The refrigerant absorbs thermal radiation in the cellar and expels it into the surrounding ground[73].

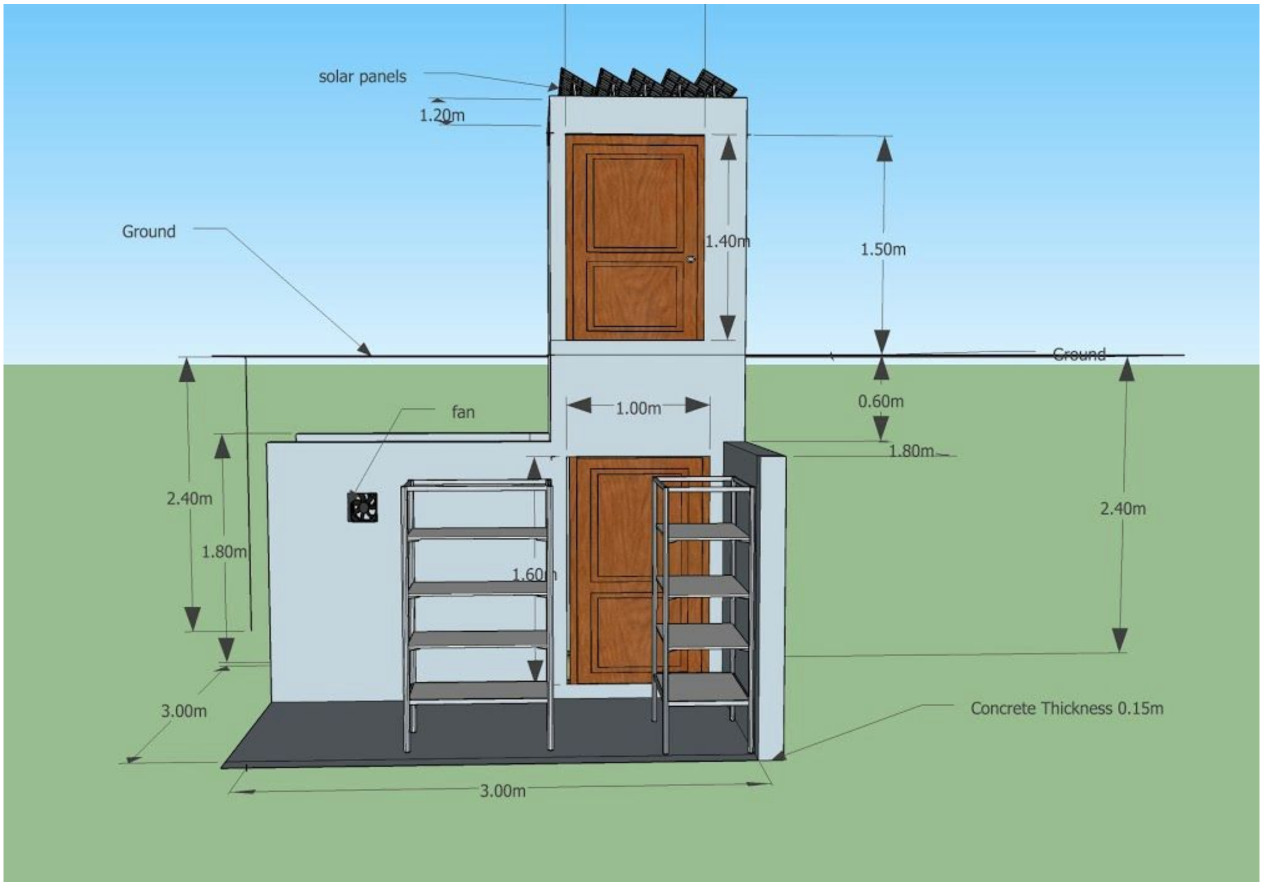

Figure 9. UCS Dimensions

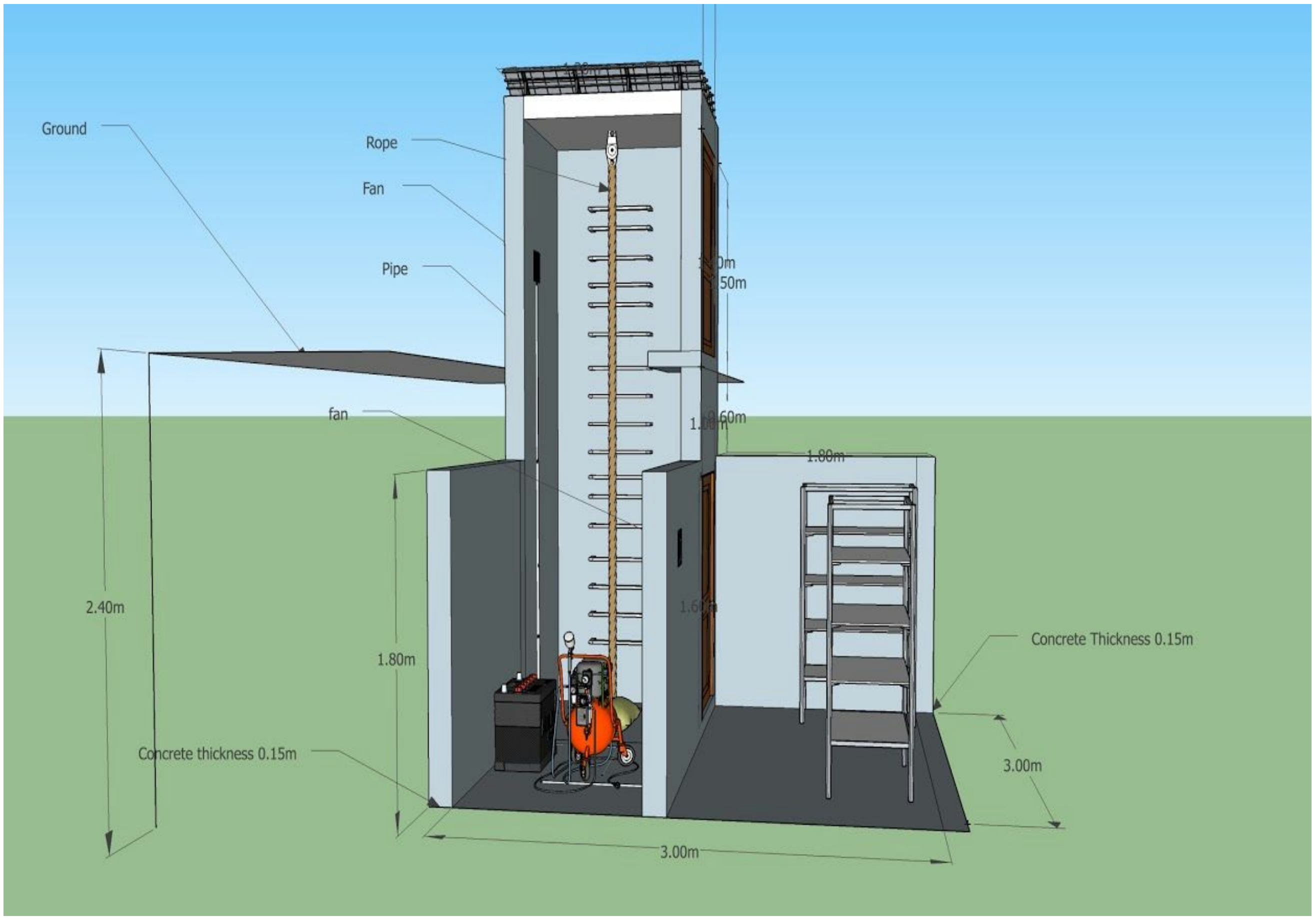

Figure 10. UCS Compressor Room and Cellar Dimensions

3.2. Plan for Detailed Design

The scope of the Final Design Specification will include:

- Instruction manual for cellar construction and maintenance
  - Installation: steps for construction
  - Operation: how to extract and store food
  - Safety precautions: possible safety risks to be made aware
- Instruction manual for air compressor
  - Installation procedures
  - Operation procedures
  - Maintenance methods
  - Safety precautions: possible risks to be made aware

3.3. Outstanding Decisions

The following decisions still need to be made:

- Type of concrete
- Placement of outer coil and compressor
- Placement and organization of storage shelves
- Battery quantity/size

3.4. Preliminary Implementation Requirements

The design implementation will primarily be done by local farmers. The client should obtain proper permits from the Ministry of Lands, Environment Council and Municipal Authority and insure farmers receive training from certified technicians before beginning the following tasks:

Table 9. Specification of Design's Implementation Procedures

Task	Description	Personnels involved	Materials	Equipment
Soil excavation	Excavate soil to begin pouring of concrete	Farmers	Soil	Shovels
Cellar wall construction	Structure and insulation of cellar	Farmers	Concrete, wood	Trowels, Buckets,
Pulley installation	Transport food in and out of cellar	Farmers	Aluminum, rope, cable	Drill, Concrete Screws
Ladder installation	Ease of entry and exit	Farmers	Iron	Drill, Concrete Screws
Light bulb installation	Provide lighting	Farmers	Light Emitting Diodes(LEDs)	Drill, Screws
Compressor installation	Cool storage temperature	Technician	2-Horsepower rotary compressor, copper pipes	Drill, Screws, Screwdrivers, welding torch
Testing	Safety measures must be approved by Municipal Authority of Mongu	Engineering department of Mongu	N/A	N/A

3.5. Preliminary Life Cycle and Environmental Impact

The design has the following life cycle:

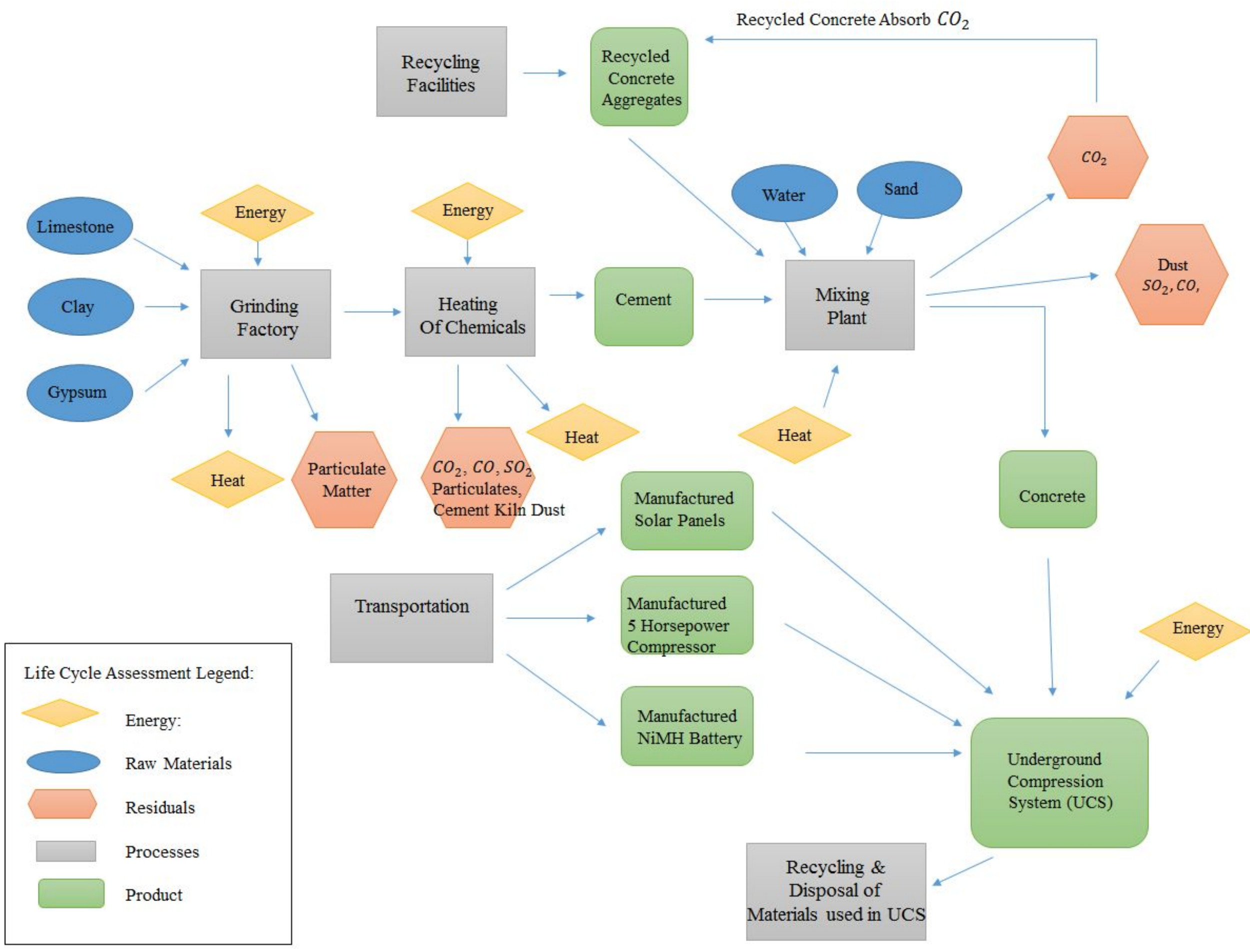

Figure 11. UCS Life Cycle

Given the UCS's nature, certain things are pre-manufactured. Hence, the solar panels and the compressor would be sourced and obtained from transportation instead of manufacturing from scratch.

The design has the following environmental impacts:

Table 10. Associated Negative and Positive Environmental Impacts

Materials/Product	Negative Impact	Positive Impact
Concrete	• Use recycled concrete to reduce greenhouse emissions from concrete manufacturing [Figure 11][86]	• Recycled concrete aggregates absorb CO_2 from surrounding environment[87]
Refrigerant	• Uses $CHClF_2$: low ozone-depletion potential, but still has global warming potential[88]	
Battery	• NiMH rechargeable batteries do not contain heavy metals which harm the environment[89]	
Solar panels, Compressor	• Production requires rare earth metal extraction, which disrupts ecosystems, and releases radionuclides, metal byproducts, dust [90][91][Appendix L] • Silicon tetrachloride and Sulfur hexafluoride-waste product from manufacturing-are potent greenhouse gases[92]	• Greenhouse gas release through life cycle lower than most electricity sources [93], around 10 times less than fossil fuel [94]

3.6. Preliminary Human Factors

The following UCS features aim to fulfills humans' needs:

- Physical
    - Cushion situated below pulley
        - Decreases falling damage
    - Ladder placed adjacent to entrance
        - Decreases falling hazard
    - "Falling Hazard" sign on door[Appendix M]
        - Decreases falling hazard
- Psychological
    - LEDs illuminates cellar
        - Alleviate achluophobia(fear for dark)
    - Cellar height: 1.8m (average male height 1.67m)
        - Alleviate claustrophobia

3.7. Preliminary Social Impact

UCS's social impact will be limited to:

Primary
- Conserve food for farmers in Mongu

Secondary
- Stakeholders
    - Zambian government
        - Follow Zambian building and environmental codes [95][96]
    - NPOs
        - Reduce poverty in Mongu by helping preserve a steady supply of food, and income when selling the food.
    - Local farmers
        - Design does not pollute local environment
        - Design meets cost objective by 90%

3.8. Preliminary Economics

The following life-cycle economic costs are based on UCS's implementation, usage and material disposal.

Table 11. Life-Cycle Economic Costs of UCS

	Capital Costs	Fixed Operating Costs	Variable Operating Costs	External Costs
Design and Implementation	**Materials** - Concrete - Copper tubing - 2-horsepower compressor - Electrical wiring - 500W solar panels - 12V batteries - Doors - LEDs - Pulley - Rope	- Digging cellar - Pouring concrete - Installing compressor - Installing tubing - Installing lights -Transportation	- Construction time	
Use		**Maintenance** - Replacement parts - LEDs - Solar panels	**None** - Power with solar panels - No external requirements	
Disposal	- LEDs - Compressor components - Concrete recycling - Compressor refrigerant	- Material transportation		- Pollution

3.9. Preliminary Test Plan

To ensure UCS meets the defined objectives, the following tests will be conducted:

Table 12. Standard Tests for Corresponding Objectives

Objective	Tests
O1.Preserve Food	● Food Safety Hazard Analysis (ISO-22000:2005 Section-7.4.3)[97] ● Test using Hurdle Technology[98]
O2.Inexpensive	● Benchmarked existing cellar costs
O3.Environmental	● Evaluation of Compliance (ISO-14001:2015 section-9.1.2.)[99] ● Determination of Asphalt Content and Gradation of Hot-Mix Asphalt Concrete (Journal of Testing and Evaluation, Vol.22, No.6)[100] ● Hazardous and Industrial Solid Waste Testing and Disposal: Sixth Volume (STP933)[101]
O4.Durability	● Method of Test for the Determination of Resistance to Stable Crack Extension Using Specimens of Low Constraint for Copper Tubing Strength (ISO-22889:2013)[102] ● Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes[103] ● Slow Strain Rate Testing for Evaluation of Environmentally Induced Cracking (STP1210)[104] ● Concrete Materials and Methods of Concrete Construction/Test Methods (A23.1-14 Section-4.3.5.2.1)[105] ● Performance and Assessment Requirements for Design Standards on Structural Concrete (ISO-19338:2014)[106]
O5.Secure	● Impact Tests (ISO-16936:2005 Section-7, Parts-1/2/3/4) for Strength of Doors[107]

4.0. Updated Project Management Plan

Table 13 specifies the milestones and due dates in the near future relevant to the client and the design team.

Table 13. List of Milestones and Associated Dates for 2016

Date	Milestone
Week of March 05	Confirm third client meeting
Week of March 14	Third client meeting, hand in Conceptual Design Specifications (CDS), client selects a final design
Week of April 24	Final Presentation

5.0 Conclusion/Recommendations

In conclusion, the need of the client is to create a cellar capable of storing produce for at least 5 months. The scope of the design is defined in section 1.0 though functions, objectives and constraints. Ideas were then generated of which 5 designs are developed in section 2.0.

The team recommends the Underground Compression system(UCS) for its compromises between cost and ability to preserve produce. The design will be presented to the client and will be edited accordingly.

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5.0. Appendices

Appendix A: Black Box Method for Generation of Functions

The black box method is used to generate functions by analyzing the most fundamental inputs and outputs of the design.

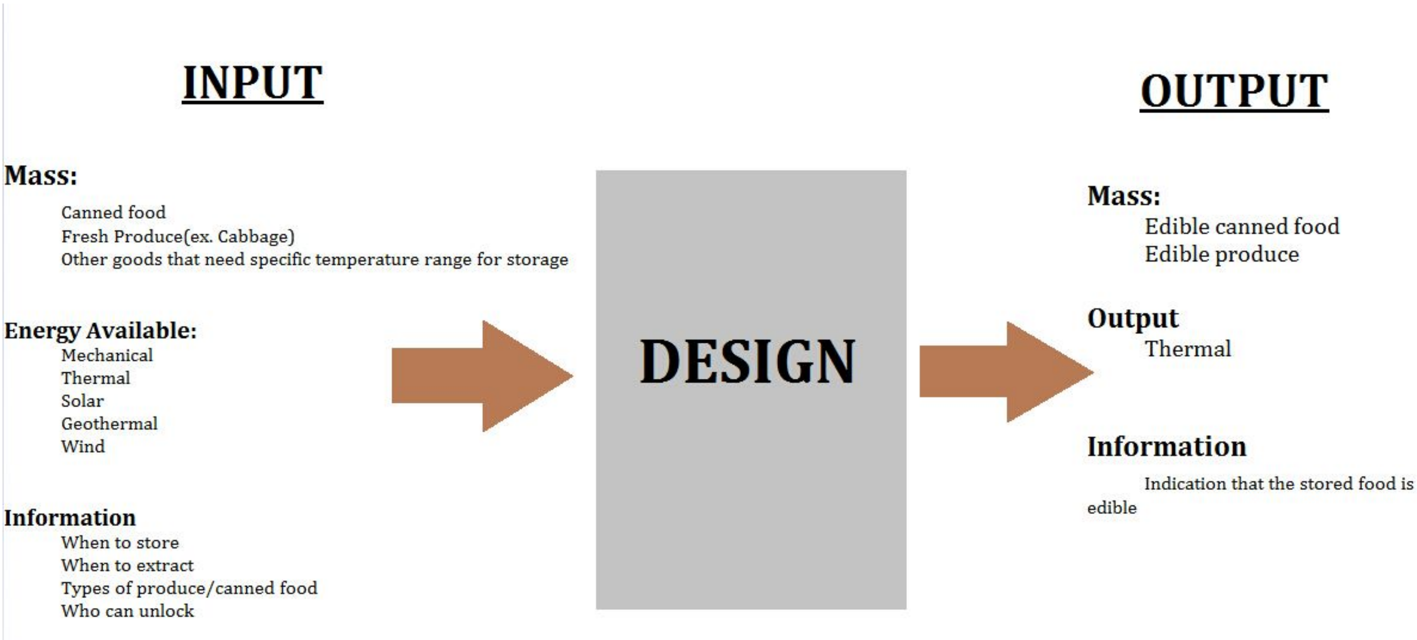

Figure A.1. Black Box Method for Generation of Functions for Cold Cellar to be Used in Mongu, Zambia

Appendix B: Methodology for Ranking and Weighting of Objectives

The list of objectives was ranked by the method of pairwise comparison based on the information obtained from the client interview and through discussion among group members. The client emphasized that the design should be economical for construction in Zambia and she greatly values environmental conservation. Objectives with a higher score are placed before the ones with lower values in descending order. Determination of the specific scores are presented in *Table B.1*. The list of objectives, after ranking, are shown in *Table B.2*.

The percentage weight of each objective is determined based on the ranking of the objectives as determined through pairwise comparison. The three top ranking objectives, "1.The design should preserve food for 5 month", "2.The design should be inexpensive", and "3.The design should have minimal environmental impact" are assigned percentage weights of 35%, 25%, and 15% respectively because the first objective is a crucial measurement of the design's ability to meet the needs of the client, the second objective is heavily encouraged by the client as SEEDS is a Canadian registered charity that operates primarily on volunteerism, while the third is strongly emphasized by the client as she is a strong advocate for environmental conservation.

Table B.1. Pairwise Comparison of Objectives

Objective	O1	O2	O3	O4	O5	O6	O7	Score	Weight (%)
The design should be secure	-	0	1	0	0	0	1	**2**	7
The design should preserve food for 5 months	1	-	1	1	1	1	1	**6**	35
The design should hold different types of produce	0	0	-	0	0	0	0	**0**	3
The design should be inexpensive	0	1	1	-	1	1	1	**5**	25
The design should be durable	1	0	1	0	-	0	1	**3**	10
The design should have minimal environmental	0	1	1	0	1	-	1	**4**	15

impact									
The design should not be reliant on external electricity	0	0	1	0	0	0	-	**1**	5

Table B.2. Objectives Listed Again in Descending Order of Importance

	List of Objectives	**Relative Weight (%)**
1	The design should preserve food for 5 months	35
2	The design should be inexpensive	25
3	The design should have minimal environmental impact	15
4	The design should be durable	10
5	The design should be secure	7
6	The design should not be reliant on external electricity	5
7	The design should hold different types of produce	3

Appendix C: Idea Generation Process for Food Cellar Designs

The design team used structured brainstorming to generate a list of 24 ideas. Then, a morphological chart--in which the row headers represent sub-functions and columns indicate various means of accomplishing the sub-functions--was used to populate the design space, yielding another 22 ideas. The 46 design ideas generated by the team are shown in Table C.1. The team members then used to multi-voting, in which each member is allocated 10 votes to vote for 10 designs of their preference. The common criteria used in casting votes among members is the design's ability to cool the storage temperature and the humidity conditions the design allows.

The multi-voting scores of each design are shown in Table C.1 in the "Total Score" column. Based on the multi-voting scores of the list of 46 designs, 7 designs with the highest votes--scoring 3 to 5 votes--were selected as candidates for the 5 alternative designs. The 7 selected designs have been bolded in Table C.1. and are again compiled in Table C.2 for clarity. Finally, consensus was used by the team to select the final 5 alternative designs for Section 2.0 Alternative Designs. The criteria used in selecting the 5 alternative designs with consensus are based on the feasibility of the design and the ability of the design to cool the storage temperature to a specific range and the ambient humidity environment that the design resides in. The results of consensus are shown in Table C.3.

Table C.1. List of Design Ideas Generated and Multi-voting Scores of Each Design

Design Ideas	Simon	Philippe	Selena	Leo	Scarlett	Total Score
1. Huge fridge system with freon cooling powered by combustion engine using natural gases			x			1
2. Half-submerged underground dissipative cooling system	x			x		2
3. Sodium Chloride with Water Reaction Cooling Mechanism						0
4. Green roof cooling system						0
5. Thermocouple cooling system		x		x		2
6. Soil cooling system with underground storage holes						0
7. Gas Law dependent closed	x					1

cooling system (PV= nRT)						
8. Underground storage unit with evaporative cooling						0
9. Half-submerged underground cellar using dissipative cooling with foam insulation	**x**			**x**	**x**	**5**
10. Multiple fans cooling system			x			1
11. MHC chip compressor cooling system with foam insulation						0
12.Canopy for Solar Insulation						0
13. Water cycle cooling system incorporated into a half-submerged underground storage unit			x			1
14. Dry the produce before storage in aboveground storage shelf						0
15. Underground cave reliant on soil humidity						0
16. Day/night heat transfer cooling system (cooler night time breeze remove heat stored in thermal mass)	**x**	**x**	**x**	**x**	**x**	**3**
17. Grass hut above ground with storage pit dug underground						0
18. Vacuum packaging of the produce before storage in a foam insulated carriage cellar			x			1
19. District cooling system at a central location with chilling water for a food cellar						0
20. Underground Compression cooling system with compressor	**x**	**x**	**x**	**x**	**x**	**5**
21. Natural gas combustion engine supplying energy to COP cooling						0

loop						
22. Double roofs and double walls with basement in cellar for storage						0
23. Storage cave submerged in a hill, using soil temperature and evaporative cooling		**x**	**x**	**x**	**x**	**4**
24. Hose air conditioning units						0
25. Liquid carbon dioxide cooling system moderated at specific storage conditions						0
26. Reflective roofs and inner storage structure within an external thermally insulated structure		x			x	2
27. Wind tower and double roofs						1
28. Central air conditioning system in multiple floors of existing building						0
29. Lithium-bromide reaction (dissipative cooling) in surface storage						0
30. Phase change materials (PCM) incorporated in building walls using latent heat		**x**	**x**	**x**	**x**	**4**
31. Radiant barriers installed on body of cellar, cellar with foam insulation						0
32. Centrally controlled air conditioning system						0
33. Building the cellar under areas of a lot of shades, with reflective material	x				x	2
34. Internal combustion engine cooling used in an above ground stone storage cellar				x	x	2

35. Multiple deeply submerged underground holes for storage of different produces	**x**	**x**	**x**		**x**	**4**
36. Vacuum insulation						0
37. Endothermic reaction cooling						0
38. Geothermal cooling using nearby river or lake	x				x	2
39. Water spray installed on top of underground cement storage cellar		x		x		2
40. Food packaging for produce to be stored in a stone cellar		x		x		2
41. Cellar with large thermal mass						0
42. Underground cooling pump embedded in a cave						0
43. Wind tower and multi-layering of storage cellar walls	**x**	**x**	**x**		**x**	**4**
44. Centrifugal cooling system with humidifier						0
45. Surface insulated foam storage with evaporative cooling device						0
46. Passive cooling tower reliant on wind and water evaporation for cooling	x					0

Table C.2. Designs Scoring 3 - 5 Votes Based on Multi-Voting Results

Selected Designs Based on Multi-Voting Results	Consensus Result
1. Half-submerged underground cellar using dissipative cooling with foam insulation	no
2. Storage cave submerged in a hill, using soil temperature and evaporative cooling with solar energy	yes

3. Day/night heat transfer cooling system (cooler night time breeze remove heat stored in thermal mass) with solar panel	yes
4. Underground Compression cooling system using ambient soil temperature with compressor powered by solar panels	yes
5. Phase change materials (PCMs) incorporated in building walls using latent heat properties with solar batteries	yes
6. Multiple deeply submerged underground holes for storage of different produces	no
7. Wind tower and multi-layering of storage cellar walls using wind energy for cooling	yes

Table C.3. Compilation of Final Five Alternative Designs

Design	Description of Design
1	Day/night heat transfer cooling system (cooler night time breeze remove heat stored in thermal mass) with solar panel
2	Storage cave submerged in a hill, using soil temperature and evaporative cooling with solar energy
3	Underground Compression cooling system using ambient soil temperature with compressor powered by solar panels
4	Phase change materials (PCMs) incorporated in building walls with solar batteries
5.	Wind tower and multi-layering of storage cellar walls using wind energy

Appendix D. Morphological Chart for Food Cellar Idea Generation

To populate the design space, the design team used a morphological chart, with rows representing subfunctions and the columns representing different means to fulfill the specified sub-functions. The morphological chart is shown in *Table D.1.* A total of 22 designs ideas were generated using the morphological chart and have been listed together with the ideas generated from structured brainstorming in *Table C.1.* of Appendix C.

Table D.1. Morphological Chart: Different Means to Meet Subfunctions

Subfunctions	Means 1	Means 2	Means 3	Means 4	Means 5
Control storage temperature	Evaporative cooling (solar energy)	Evaporative cooling+soil (wind power)	Underground cooling pump/ deep ground Temperature	Thick insulation+large thermal capacity	Vapor compression system
Control moisture	ground level variation	Self humidify with cooling system	dehumidifier for heavy duty humidity control	water spray	electronic steam humidifiers
Protect food from external contamination	Termite, rat resistant materials	Moisture-resistant materials ex.cement, plaster	Two separate sealed entrances (surface/cellar ceiling)	Multiple material layerings	Packaging material on food (wrappings)
Store food (storage)	Shelves on walls	Ground base shelves	Sealed subsections for food	Drawers	Different containers, multiple storage rooms
Insert and extract food	manual extraction by hand	manual extraction (exit at ground level)	pulley/rail system	Electronic extraction system	baskets & backpacks
Prevent unauthorized extraction of food (people)	locked outer entrance	underground, front door locked with key	gates, grates	locks: electronic, combination, master key	pushbutton mechanical deadbolt

Appendix E. Criteria for Evaluation of Objectives

Table E.1. specifies the correspondent meaning of the percentage values assigned when the team is evaluating the designs against the specified objectives.

Table E.1. Correspondent Criteria for Evaluation of Objectives

Percentage Met (%)	Correspondent Meaning of Assigned Values
0	Feature fails to meet objective completely
33	Feature has elements that meet the objective, but is still inadequate
66	Feature barely meets the corresponding objective
100	Feature completely fulfills and exceeds the corresponding objective

Appendix F. Storage Capacity, Cost, and Temperature Calculations of Hillside Evaporative Cooling Cellar

Dimension (Length x Width x Height)
exterior dimensions: 3.9m x 1.9m x 1.9m   interior dimensions: 3.5m x 1.5m x 1.5m

Material Cost Calculation:

fan:	15$ [108]
pipes:	50$ [109]
light:	35$ [110]
solar panel:	30$ [111]
Battery:	55$ [112]
Concrete*:	760$
Wire:	5$ [113]
<u>Total:</u>	<u>950$</u>

*1.9m x 1.9m x 3.9m - 1.5m x 1.5m x 3.5m) x 122$/m^3=~760$ [114]

Storage capacity:
3.5m x 1.5m x 1.5m = 6.2m^3

Storage Temperature estimates:

Soil temperature:	16ºC	[75]
Latent heat of evaporation:	2257kJ/kg	[115]
Heat capacity:	1.0kJ/kgK	[116]
Saturation of water in air:	10g/kg at 16ºC	[117]
Humidity:	50%	[1.6]
Remaining capacity:	5g/kg	

$E=h_e m$	$\Delta T= E/mc$	$T= T_0 - \Delta T$
E=2257kJ/kg x 0.005kg	ΔT= 11.3kJ /(1.0 kg x 1.0 kJ/kgK)	T= 16ºC - 11ºC
E= 11.3 kJ	ΔT= 11.3ºC	**T= 5ºC**

Cellar air temperature: estimates show that storage temperature can be maintained at **5ºC**

Ceiling Strength calculation:

$$F = \rho g d A \qquad \sigma_{3\ point} = \frac{3FL}{2bd^2}$$

$$F = 1905\frac{kg}{m^3} \times 1m \times 9.8\frac{m}{s^2} \times 9m^2 \qquad \sigma_{3\ point} = \frac{3\times 138000N \times 950mm}{2\times 1900mm \times (150mm)^2}$$

$$F = 138kN$$

Appendix G. Cost, Storage Capacity Calculations of Reflective Wind Tower

Above ground structure:

- Geodesic dome
  - Interior: 1 meter radius
  - Exterior: 1.2 meter radius
- Towers (Lenght x Width x Height)
  - Interior: 1 meter x 1 meter x 2 meter
  - Exterior: 1.3 meter x 1.3 meter x 4.2 meter
  - Number: 2

Below ground structure:

- Cylinder
  - Interior: height of 1m, radius of 1 meter
  - Exterior: height of 1.2m, radius of 1.2 meter

Storage capacity:

Cylinder: $pi * (1m)^2 * 1m = 3.14\ m^3$

Hemisphere: $2 * pi * (1m)^3 / 3 = 2.09m^3$

Total: $3.14m^3 + 2.09m^3 = 5.23m^3$

Temperature Lowering Calculations:

Effective parameters for comfort	Model 1	2	3
Fall of temperature from 40 °c	29.3	30.8	32.2

Figure H.1. taken from *Analysis on Iranian Wind Catcher and Its Effect on Natural Ventilation as a Solution towards Sustainable Architecture*[70] to calculate change in temperature by wind towers.

Percent of Decrease in Temperature:

100% x (1 - (29.3+30.8+32.2)K/(3x40K)) = **23%**

Concrete cost:

Concrete cost/m^3: $122\$/m^3$ [118]

4 wind tower $2*(4.8*(1.3m)^2 -4.5*(1m)^2) = 7.22m^3$

Hemisphere $2 * 3.14*((1.2m)^3 - (1m)^3)/3 = 1.52m^3$

Cylinder $pi * ((1.2m)^3 - (1m)^3) = 2.29m^3$

Total volume	7.22 + 1.52 + 2.29 = $11.03m^3$
Cost	$11.03m^3$ * 122 $/$m^3$ = 1345.66 $

Reflective materials

Hemisphere Cost: 2*3.14*100=$628

Material Cost Calculations

Security door	200$ [119]
Reflective materials	628$
Concrete	1345.66$
<u>total</u>	<u>2173.66$</u>

Appendix H. Cost, and Storage Capacity Calculations of Night Breeze Cooling Cellar

Dimension (Length x Width x Height)

above ground dimensions: 3.2m x 3.2m x 1.5m

underground dimensions: 3.2m x 3.2m x 0.9m

Cost estimate:

spray foam insulation	-$0.7per board foot [120][121]
solar panel	-$315 [122]
portland cement	-$51-55 per ton[123]
nightbreeze system	-$2,850[124]

Portland Cement Volume:

flooring +ceiling:	$(3.2m \times 3.2m \times 0.1m) \times 2 = 2.05m^3$
walls:	$(3.2m \times 2.4m \times 0.1m) \times 4 = 3.07m^3$
entrance:	$(1m \times 0.9m \times 0.04m) \times 2 = 0.072m^3$
total:	$2.05m^3 + 3.07m^3 - 0.072m^3 = 5.05m^3$

$5.05m^3 = 6.61yard^3$

$6.61yard^3 = 1.78ton$

3.2m= 10.5 foot

250 british pounds= $480

1.78ton x $55/ton + $315 +$2850+ 10.5m x 10.5m x$0.7/board feet= $3,340

Storage Capacity: 3.2m x 3.2m x 2.4m-0.36m x 0.15m x 1.25m x 2-2.9m x 1.2m x 1.5m-3.2m x 3.2m x 0.7m $=12.0m^3$

Appendix I: Cost, Load, and Stress Calculations of Underground Compression System

Concrete cost (25cm walls)[114]

floor + ceiling	$(3m \times 3m \times 0.15m) \times 2 = 2.70\text{m}^3$
walls	$((3.3m \times 3.3m) - (3m \times 3m)) \times 1.8m = 3.402m^3$
Shaft+entrance	$((1.5m \times 1.5m) - (1.2m \times 1.2m)) \times 2.2m = 1.8m^3$
Total	$2.7m^3 + 3.402m^3 + 1.8m^3 = 7.902m^3 \times 122\frac{\$}{m^3} = 962\$$

Cost Calculations

1-fan (for humidifier)	- 15$	[125]
3-light fixtures	- 100$	[126]
1-2-horsepower compressor	- 200$	[127]
2-500 watt solar panels	- 570$	[128][129]
30ft-¼" copper tubing	- 30$	[130]
2-12V batteries	- 200$	[131]
$7.802m^3$ concrete	- 962$	[132]
total	- 2077$	

Calculations of Underground Compression System's Ceiling Stress:

$$F = \rho g d A$$

$$F = 1905\frac{kg}{m^3} \times 0.6m \times 9.8\frac{m}{s^2} \times 9m^2$$

$$F = 168kN$$

$$\sigma_{3\,point} = \frac{3FL}{2bd^2}$$

$$\sigma_{3\,point} = \frac{3 \times 168000N \times 1500mm}{2 \times 3000mm \times (150mm)^2}$$

$$\sigma_{3\,point} = 5.85MPa$$

Appendix J. Cost, and Storage Capacity Calculations of PCM Layered Storage System

Material Volume Calculations:

Clay brick volume: $(0.1m \times 10m \times 1.8m) + (3m \times 0.2m \times 0.1m) \times 2 + 2 \times (0.2m \times 2m \times 0.9m)$
$= 2.28\ \text{m}^3$

PCM volume: $(0.02m \times 10m \times 1.8m) = 0.36\text{m}^3$

Cost Calculations

Reflective coating	- 21$ [133]		
PCM	- 2844$	from	7.9$ per kilogram[134]
Clay bricks	- 130$	from	56.56$ per m^3[135]
3 Humidifiers	- 120$[79]		
<u>total</u>	<u>- 3,115$</u>		

*Note: cost of PCM per kilogram is found by taking the average value of the range between 3.30$/kg and 12.50$/kg[134], which is approximated to 7.9$/kg, the density of the PCM is assumed to resemble that of water: 1000kg/m^3

Storage Capacity:

Interior volume = $(2.5m \times 1.5m \times 1.8m) + (0.2m \times 2.5m \times 1.8m) \times 0.5 = 7.2\ \text{m}^3$

Appendix K. Weighted Decision Making Matrix for Selection of Proposed Conceptual Design

The design team used the weighted decision making matrix to evaluate the 5 alternative designs. The method for determination of the weighting of each objective is specified in Appendix B. Methodology for Ranking of Objectives. The relative percentages of each objective are listed again in Table K.2. for clarity.

The scores of the different objectives of each alternative design is calculated by multiplying its percentage met values-which are specified throughout sections 2.1-2.5 and again listed in Table K.1. for clarity. Each design met the specified objectives to different extents. The correspondent scores of each objective of each alternative design has been calculated and compiled in Table K.2. The total scores of the objectives of each alternative design is found by finding the sum of the percentage scores of each objective. The final score of each alternative design is listed in Table K.3.

The collective results indicate that **Design 2.4. The Underground Compression System** best meets the needs of the client with its superior performance in achieving the best balance between the cost of the design and the design's functionality in fulfilling the need to preserve produce for 5 months, which is achieved through the control of the cellar's storage temperature and relative humidity. The weighting also indicates that the Underground Compression System has an overall score of 94.4%, which is 7.1% higher than the next highest-scoring design of the 5 alternative designs.

Table K.1. Percentage Met Values of Each Objective in the Alternative Designs

Objective	Percentage Met Values (%)				
	Design 2.1	Design 2.2	Design 2.3	Design 2.4	Design 2.5
O1	70	70	65	100	70
O2	100	80	85	90	65
O3	90	90	95	90	80
O4	100	95	100	100	90
O5	90	80	90	90	100
O6	100	100	100	100	100

O7	100	80	70	70	95

Table K.2. Scoring of Each Objectives for the Five Alternative Designs Based using Weighted Matrix Method

Objective	Relative weight of objective (%)	Design 2.1 (%)	Design 2.2 (%)	Design 2.3 (%)	Design 2.4 (%)	Design 2.5 (%)
O1	35	24.5	24.5	22.75	35	24.5
O2	25	25	20	21.25	22.5	17.5
O3	15	13.5	13.5	14.25	13.5	12
O4	10	10	9.5	10	10	9
O5	7	6.3	5.6	6.3	6.3	7
O6	5	5	5	5	5	5
O7	3	3	2.4	2.1	2.1	2.85

Table K.3. Compiled Total Score of Each Alternative Design

Alternative Design	Score (%)
2.1. Hillside Evaporative Cooling Cellar	87.3
2.2. Reflective Wind Tower Storage Cellar	80.5
2.3. Night Breeze Cooling System	81.65
2.4. Underground Compression System	**94.4**
2.5. PCM Layered Storage System	77.85

Appendix L. Life Cycle Assessment of Photovoltaic Systems

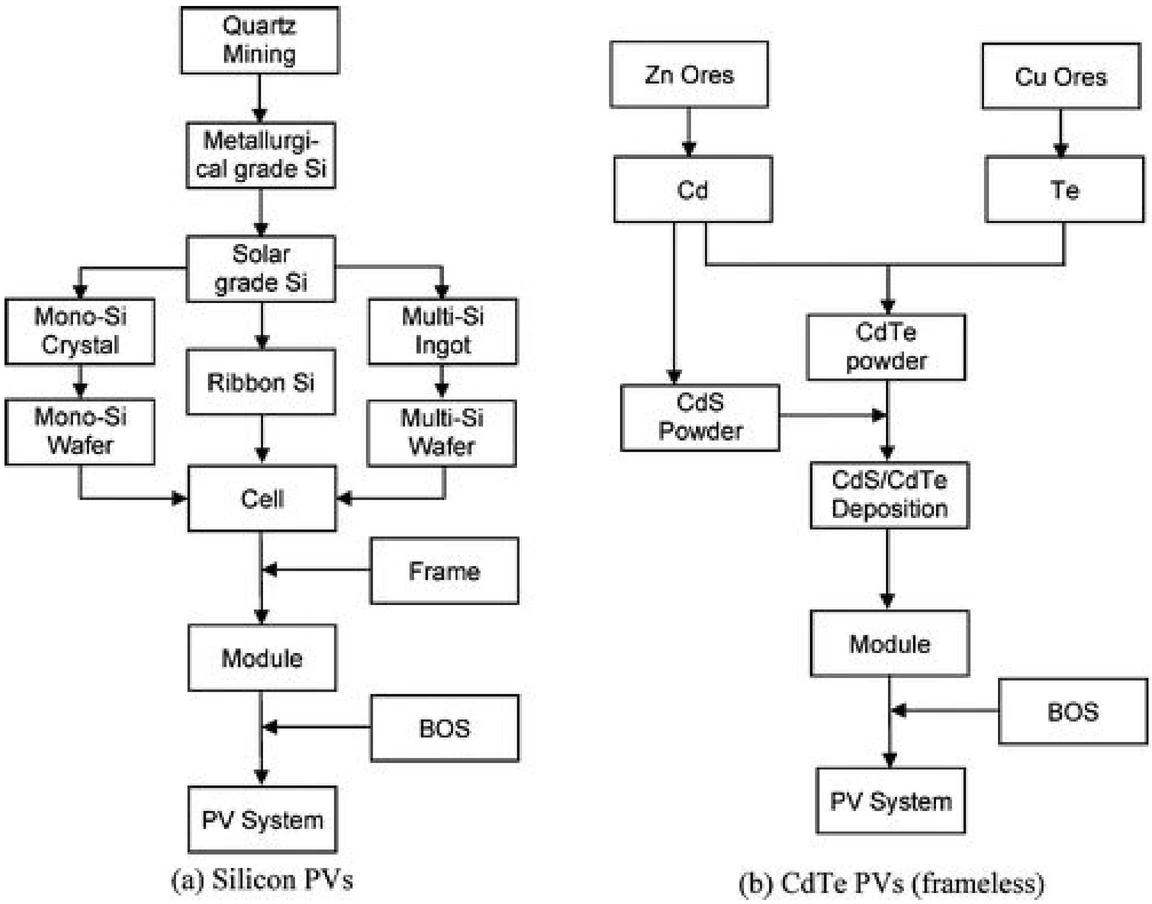

Figure L.1. Life Cycle Assessment Diagram of Typical PhotoVoltaic Systems(Solar Panels) [136].

Appendix M. Caution Sign for Falling Hazard.

Figure M.1. Caution Sign for Falling Hazard Placed on the Entrance Door of the Underground Compression System Cellar Design [137]