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Turbine House: A Net-zero Energy House

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A Capstone Project Submitted in Partial Fulfillment of the Requirements of the Renee Crown University Honors Program at Syracuse University

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Abstract

Current use of fossil fuels has raised adverse problems in today's society. The biggest one of them is the climate change caused by emissions of greenhouse gases. For this reason, renewable energies, or energy flows which are replenished at the same rate as they are used, are needed to reduce carbon emissions in the range of 60-80% by the end of the twenty-first century. [1] Energy used in houses nationwide contributes to 16% of generated greenhouse gas emissions. [3] This large percentage of greenhouse emissions could be reduced by designing and developing energy efficient houses, or net-zero energy houses, such as the Turbine House. The Turbine House combines wind energy, solar photovoltaic energy, solar thermal energy, and geothermal energy to offer a fully integrated sustainable solution for off-the-grid living. The design was developed by Prof. Michael Pelken from the School of Architecture and Dr. Thong Dang, from LC Smith College of Engineering. The main goal of this project is to perform sizing calculations to adjust preliminary design dimensions for both renewable energy technologies and treated floor area to obtain a net-zero energy house. Features of the passive house standard, an energy performance standard, will be implemented to maintain primary energy consumption under 120kWh/m^{2}year, and space heating consumption under 15kWh/m^{2}year. Environmental, architectural and system variables were taken into account for site specific energy analysis of the Turbine House located at Cape Cod, Massachusetts. RETScreen software was utilized to analyze site specific conditions and perform sizing calculations for geothermal heat pump. As a result, wind energy contributes 66% of renewable energy provided, while solar photovoltaic energy and solar thermal energy contributes 33% of renewable energy provided. Geothermal energy will be utilized as a back-up option for space heating and domestic water heating.

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Acknowledgements

My deepest gratitude goes to Prof. Michael Pelken, my faculty advisor from the School of Architecture, for his weekly advice that contributed to the development of the “Turbine House”, as well as the “Self-sustaining Street Light.” I would also like to thank Prof. Thong Dang, from the Mechanical and Aerospace Engineering department, for his continuous support and advice. A special thank goes to Seth King, graduate architecture student, for his collaboration on the design of the Turbine House. Finally, I would like to thank Renee Crown Honors faculty advisors for being encouraging and understanding throughout this process.

1. Introduction

1.1 Low Energy House

Low Energy House is usually referred to homes that consume less energy than standard homes within that country. In Germany, to achieve Low Energy House (LEH) standard the annual heat consumption of the house must be less than 70 kWh/m²year, which is less than 50% of required energy consumption by the 1984 German Ordinance. [2] This value can be compared to the energy consumption of 168.5 kWh/m²year of a Typical U.S. Household. These values were taken from the U.S. Energy Information Administration website, www.eia.doe.gov, based on the Residential Energy Consumption Survey (RECS) of 2005. These are approximate values, assuming that the treated floor area is 201.8m² for a typical U.S. Household. The end-use consumption of electricity for a typical U.S. household are summarized below.

Figure 1 Typical U.S. Household Primary Energy consumption

Primary Energy Consumed	
Space Heating, Natural Gas	68.8 kWh/m²year
Air Conditioning	17.2 kWh/m²year
Domestic Water Heating, Natural Gas	32.3 kWh/m²year
Electrical Appliances (incl. lighting, refrigeration, cooking, washing, etc.)	36.3 kWh/m²year
Specific Primary Energy consumption	**168.5 kWh/m²**

In United States, to comply with ENERGY STAR standard, a house must meet strict energy efficiency guidelines set by U.S. Environmental Protection Agency (EPA). These homes save at least 15% on energy consumption compared to the 2004 International Residential Code (IRC), by utilizing energy efficient appliances that are labeled by ENERGY STAR, which typically makes the house 20-30% more efficient than standard homes. [3]

1.2 Ultra-low Energy House

Ultra-low energy house standards refer to standards that have energy requirements lower than the requirements for Low Energy House standard, such as Passive House standard. The Passive House standard, or PassivHaus, refers to a voluntary, low energy construction standard, developed by Dr. Wolfgang Feist of the PassivHaus Institut in Darmstadt, Germany. Buildings that follow this standard have been built in Germany, Austria, Switzerland, UK and USA. [4]

1.2.1 Passive House Standard

A Passive House is a building in which the "heat requirement is so low that a separate heating system is not necessary and there is no loss of comfort," according to Dr. Wolfgang Feist. Compared to previously mentioned Low Energy House standard and Energy Star standard, Passive House standard is an energy performance based standard instead of a prescriptive one. The Turbine House will follow Passive House standard guidelines to attain an energy efficient house whose specific primary energy consumption is less than 120 kWh/m^{2}year, and annual space heating energy is less than 15 kWh/ m^{2}year. Some of the recommended features that are required within the house to achieve an ultra-low energy house are summarized in Figure 2.

Figure 2 Passive House Performance Features [28]

Energy Performance Features	
Passive Solar Gain	
Superglazing	Low-emissivity triple glazing: U-value < 0.75 W/(m²K), solar
Superframes	Superinsulated window frames, U-value<0.8 W/(m²K)
Optimized south-facing glazing	40% of total heat demand
Superinsulation	
Building Shell	U- value ca. 0.1 W/(m²K)
Building Element Junctions	Thermal-bridge-free construction: linear thermal
Airtight Building Envelope	Less than 0.6 air changes per hour at n50
Mechanical Ventilation Heat Recovery	
Hygienic Ventilation	Directed air flow through whole building; exhaust air
Heat Recovery	Counterflow air-to-air heat exchanger: heat transfer
Latent Heat Recovery from Exhaust Air	Compact heat pump unit

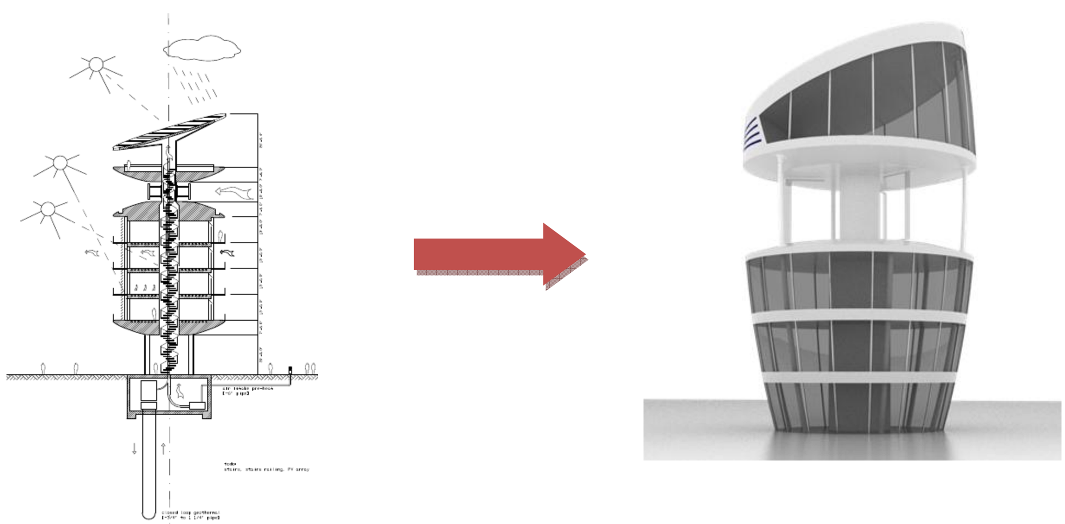
1.3 Net-Zero Energy House

According to the European Parliament, which recently approved a recast of the Energy Performance of buildings Directive, a net-zero energy building is defined as "a building where, as a result of the very high level of energy efficiency of the building, the overall annual primary energy consumption is equal to or less than the energy production from renewable energy sources on site" [5] This definition was utilized to analyze energy balance in the Turbine House.

A net-zero energy house can be connected to the grid or disconnected from the grid. If it is connected to the grid, energy produced by the renewable energies within the house is sold to the grid. To obtain a net-zero energy house, the amount of energy sold annually to the grid must be equal or more than the amount of energy consumed by the house. If disconnected from the grid, energy consumed is provided entirely by energy sources connected to the house. Off-the-grid housing requires an on-site electric storage system to store energy generated at site, and consume it when necessary. [6] Currently, most common approach to attain a net-zero energy house is to use the electricity grid both as a source and a sink of electricity, thus avoiding the on-site electric storage systems. [7] The Turbine House can choose from being off-the –grid or connected to the grid.

1.4 The Turbine House

The Turbine House is a unique and fully integrated sustainable solution for off-the-grid living. It combines wind energy, solar photovoltaic energy, solar thermal energy, and geothermal energy to provide electricity to the house. The main goal of this project is to adjust preliminary dimensions of renewable energy technologies and treated floor area to obtain a net-zero energy balance house. Shown in The preliminary design, shown in Figure 1a has a total treated floor area of 632m², and the final design shown in Figure 1b has a total treated floor area of 111m². Total treated floor area was modified to obtain a more compact design to go along with Passive House guideline for a compact and airtight building envelope. The designs were both developed by Professor Michael Pelken from Syracuse University School of Architecture.



(a) (b)

Figure 3Turbine House: (a) Preliminary Design, (b) Final Design [10]

2. Methodology

2.1 System Variables

The Turbine House combines Wind Energy, Solar Thermal Energy, Solar Photovoltaic Energy and Geothermal Energy to obtain a net-zero energy house. All these variables previously mentioned are highly dependent on environmental variables and architectural variables. To perform energy analysis on all these system variables, primary energy was chosen as an indicator for annual energy use in the house. It takes into account difference between electricity and fossil fuel use and includes efficiency of delivered space heating, lighting, appliances and domestic hot water. To incorporate renewable energy generation, a non-fossil source, into energy system model, the output of the conversion technology is assumed to be the primary energy.

Required primary energy consumption of the house was estimated to be the maximum primary energy allowed for Passive House certificate, 120 kWh/m^{2}year. The maximum allowable peak heat demand was assumed to be 12 W/m^2, different from the Passive House peak demand of 10 W/m^2. This change was made to adjust Passive House Standard, a German standard, to United States extreme weather. [8] Steady-state heat loss and semi-static monthly energy demand were assumed, to perform energy calculations of annual energy use of the Turbine House. In energy calculations, energy figures are stated in kWh.

2.2 Environmental Variables

Renewable energy technologies are highly dependent on renewable energy resources such as wind and solar radiation. Wind power was analyzed for different wind speeds, and solar thermal energy and solar photovoltaic energy was analyzed for different full sunlight hours. To obtain a more realistic energy analysis, a site location was chosen.

2.2.1 Site Location

Average wind speeds were the main parameter taken into account since potential wind power density is highly directly proportional to wind speed cubed. The U.S. Department of Energy classifies wind power at 10m and 50m above the ground, and categorizes site locations with respective wind power class, shown in Figure 4.

Table 1-1 Classes of wind power density at 10 m and 50 m[(a)].

Wind Power Class*	10 m (33 ft) Wind Power Density (W/m^2)	10 m (33 ft) Speed[(b)] m/s (mph)	50 m (164 ft) Wind Power Density (W/m^2)	50 m (164 ft) Speed[(b)] m/s (mph)
1	0	0	0	0
2	100	4.4 (9.8)	200	5.6 (12.5)
3	150	5.1 (11.5)	300	6.4 (14.3)
4	200	5.6 (12.5)	400	7.0 (15.7)
5	250	6.0 (13.4)	500	7.5 (16.8)
6	300	6.4 (14.3)	600	8.0 (17.9)
7	400	7.0 (15.7)	800	8.8 (19.7)
	1000	9.4 (21.1)	2000	11.9 (26.6)

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 3%/1000 m (5%/5000 ft) elevation.

Figure 4 Classes of Wind Power Density [11]

Site locations along the U.S. coast were taken into account, selecting the ones with highest wind power class. Wind power class of California, Northeast coast and South east coast were taken into account. Annual average wind power for these locations can be compared with United States map in Figure 5. In this map, the darkest regions are the ones with higher wind speed densities. It can be observed that Southeast coast or California do not have as much wind energy potential as the Northeast coast, or Cape Cod, Massachusetts.

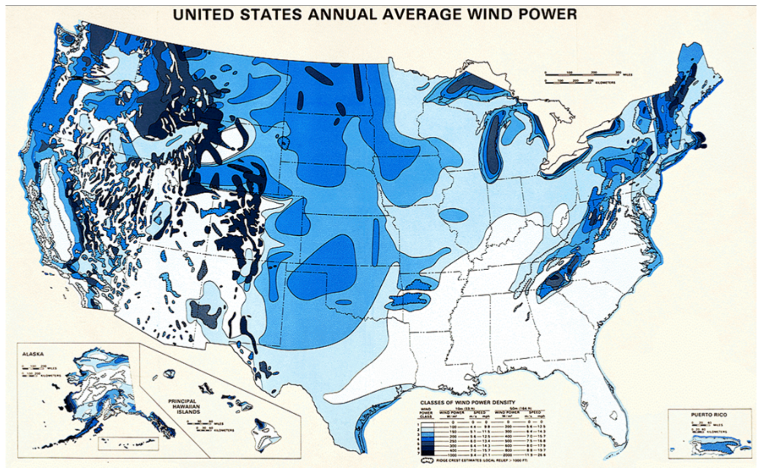


Figure 5 United States Annual Average Wind Power [12]

Cape Cod, Massachusetts, was selected for its proximity to the coast and being one of the areas with “highest wind energy potential” according to research done by National Renewable Energy Laboratory, sponsored by the Department of Energy, with wind power class of 5 and 6, shown in Figure 6 .

The average wind speed at 10m above ground was utilized for wind power calculations, since it is similar to the height if the Turbine House wind turbine. According to NREL, winter is the season of maximum wind power throughout the Northeast region, while summer is the season of minimum wind power. [11]

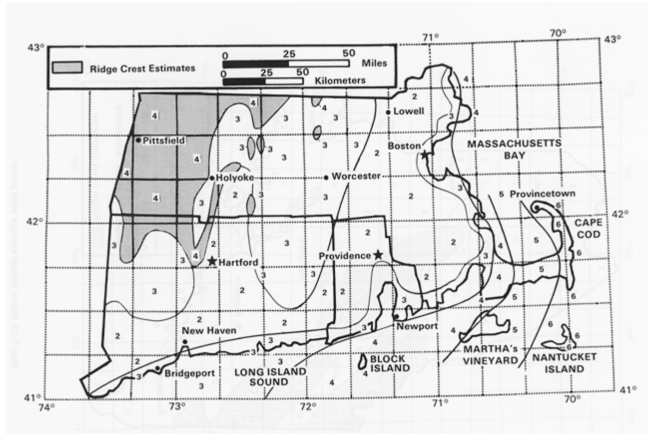


Figure 6 Conneticut, Massachusetts, and Rhode Island annual average wind power [11]

Cape Cod, Massachusetts, represents an ideal site location for the Turbine House. After evaluating wind power potential and solar radiation incidence, geothermal energy potential was analyzed using RETScreen software.

2.2.2 RETScreen Software

The RETScreen Clean Energy Project Analysis Software is used to "evaluate the energy production and savings, costs, emission reductions, financial viability and risk for various types of Renewable-energy and Energy-efficient Technologies (RETs)." [13] The RETScreen Climate Database provides data from ground monitoring stations and/or from NASA's global satellite/analysis data. This software was utilized to perform sizing calculations for geothermal heat pump at Cape Cod, Massachusetts, utilizing both ground and NASA sources to evaluate land area and borehole size for all different types of soil, since information for specific type of soil at Cape Cod was not acquired.

2.3 Architectural Variables

Architectural variables such as treated floor space area, building envelope, type of glazing within the house and its position regarding cardinal directions are also important and taken into account when designing an energy-efficient building. Since Passive House standard is a German standard, the method used to calculate treated floor space area is different in Germany is different from the one used in United States. The method used in Germany was utilized, which takes into account only the area that is being used and requires space heating. It does not take into account circulation area or wall area. [8] The main purpose architectural variables are taken into account is to optimize solar gain, maintaining a balance so that the house does not overheat. The dependence of these variables are further explained in the Passive House standard, where these play an essential role to reduce space heating energy consumption.

3. Wind Power

3.1 Rotor Type Selection

For the Turbine House, two types of wind turbine were examined: the vertical-axis wind turbine (VAWT) and the horizontal-axis wind turbine (HAWT). The vertical-axis wind turbine was selected as a method of producing wind energy. The axial symmetry provided by A VAWT was ideal for the Turbine House design, which provides synergistic integration and aesthetic. VAWTs also provide significant benefits from their ability to accept wind from any direction; there is no need for a VAWT to change orientation through the use of a directional vane, as with a HAWT.

Two types of vertical axis wind turbines were analyzed to provide optimal performance and maximum wind power: lift-based designs (e.g., Darrieus rotors and H-rotors) and drag-based designs (e.g., Savonius rotors). Darrieus-type rotors offer significantly efficient benefits over Savonius rotors. The Darrieus-type rotors are able to maintain peak efficiency over a wider range of tip-speed ratios than Savonius-type rotors, as seen in Figure 7. Additionally, Savonius rotors rotate at much lower rotational speeds, and have lower cut-in wind speeds capable of overcoming the starting torque requirements of the attached generator. As a result, Savonius rotors have not yet proven themselves worthy of producing electricity on a large scale like Darrieus rotors have.

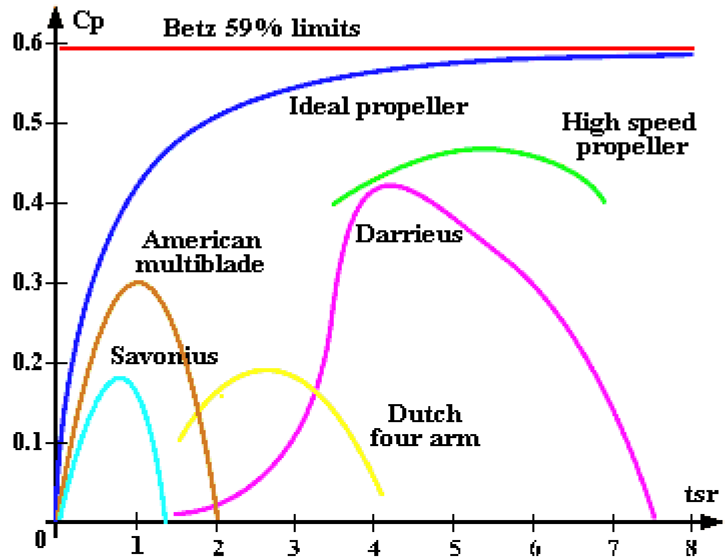


Figure 7 Power Coefficient Curves for various wind turbine designs [9]

Based on efficiency benefits of Darrieus-type rotor previously mentioned, Darrieus-type rotor was chosen to be integrated at the top of the Turbine House as seen in Figure 1b.

3.2 Converging Section

According to the United States Patent Application, one of the fundamental design points of the Turbine House is the inclusion of "…a series of plates located above and below each turbine for focusing and converging the wind inwardly. The plates are aerodynamically-designed to converge the wind onto the turbine and provide a strong wind current" This convergence is applicable to the design, not only for aesthetic improvement, but for increasing the velocity of the useful air flow. [10] As shown in equation of wind turbine power,

$$P = \frac{1}{2} \cdot \epsilon \rho V^3 A_S \qquad (1)$$

Where ϵ is wind turbine efficiency, ρ is air density, V is incoming wind speed, and A_s is wind turbine cross sectional area, wind turbine power varies with velocity raised to the third power V^3. Accordingly, an increase of wind velocity by a factor of two could correlate to an increase of power by a factor of eight.

The principle of velocity convergence is derived from the assumption of a flow tube theory for one-dimensional isentropic flow. From this assumption, the continuity equation can be applied as shown in Equation (2). Through the visual representation displayed in Figure 8 and the application of Equation (2) for steady-state flows, the simple relation of Equation (3) is attainable. For the low velocity, incompressible flows under consideration, it is assumed that the density at state one is equal to the density at state two, leading to the reduction provided in Equation (4). Rearranging the formula of Equation (4) leads to the final result in Equation (5) showing that the velocity at state two is a function of the area ratio. Moreover, this leads to the determination that a velocity increase is attainable through desirable condition described in Equation (5). This velocity increase is taken into account in wind energy calculations, which increases wind turbine efficiency to a maximum of 0.4.

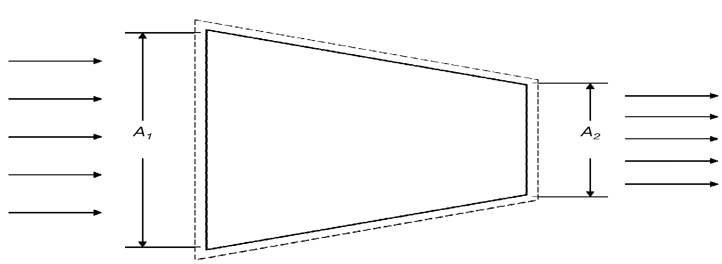


Figure 8 Convergence Section

$$\frac{\partial}{\partial t}\oint_{CV}\rho dV + \oint_{CS}\rho\vec{V}dA = 0 \quad (2)$$

$$\rho_1 V_1 A_1 = \rho_2 V_2 A_2 \quad (3)$$

$$V_1 A_1 = V_2 A_2 \quad (4)$$

$$V_2 = V_1 \frac{A_1}{A_2} \quad (5)$$

$$\therefore V_2 > V_1, \frac{A_1}{A_2} > 1 \quad (6)$$

3.3 Energy Analysis for Wind Turbine

Wind Energy in the Turbine House was analyzed for various wind speeds. Equation (1) was utilized to perform this analysis, and energy efficiency including amplification effect of housing converging section was 0.4. Table 3 summarizes other constraints taken into account to calculate wind power. Wind capacity refers to the amount of wind available in a day, which is approximately 90% of the day. The dimensions for the wind turbine were provided by Seth King, architecture graduate student, from previous proportions of the Turbine House determined by Prof. Michael Pelken. Wind power was analyzed to guarantee that, along with other renewable energy technologies, it would provide a sufficient energy to power a fraction of the Turbine House.

Figure 9 Wind Turbine Constraints

WIND TURBINE CONSTRAINTS				
Wind Capacity	0.9		0.9	
Hours/year	8760	h/year	8760	h/year
Air density	0.077	lb/ft^3	1.23	kg/m^3
Wind Turbine Area	285	ft^2	26.49	m^2

4.0 Solar Thermal Energy

As already mentioned, the sun is one of the most important renewable energy sources. In the Turbine House, two methods to gather thermal or heat energy are employed: Active Solar Heating and Passive Solar Heating. The ultimate goal of implementing solar thermal energy is to reduce domestic hot water and space heating demand.

4.1 Active Solar Heating

Active Solar Heating involves the use of a solar collector mounted on the roof of a building. In the Turbine House, solar collectors will occupy a fraction of the area of the circular tilted roof also containing photovoltaic panels. Heat utilized will be at low temperature (under 100° C) used for domestic hot water.

Solar collectors utilized for water heating are commonly categorized as: low-temperature, or medium-temperature. Medium-temperature systems were chosen to be implemented in the Turbine House, since low-temperature systems are mostly used for pool heating purposes. Medium-temperature systems generate temperatures from 110-180°F (43-82°C).

Medium-Temperature systems are available in a variety of models, such as: Flat Plate Collectors, Vacuum Flat Plate Collectors and Evacuated tube collectors. Figure 11 Evacuated Tubes Solar Collector System below shows a graph with the different efficiency of these three types of solar collectors.

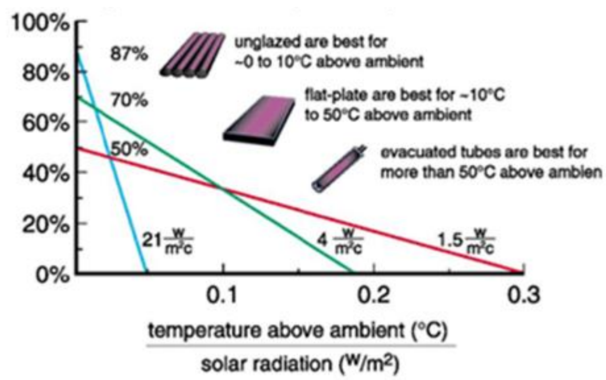


Figure 10 Solar Collector Efficiency [12]

Evacuated Tube Collector was chosen because of its higher efficiency compared to Flat Tube Collector, as seen in Figure 11above. System design for Evacuated Tubes solar collector is shown below, Figure 11.

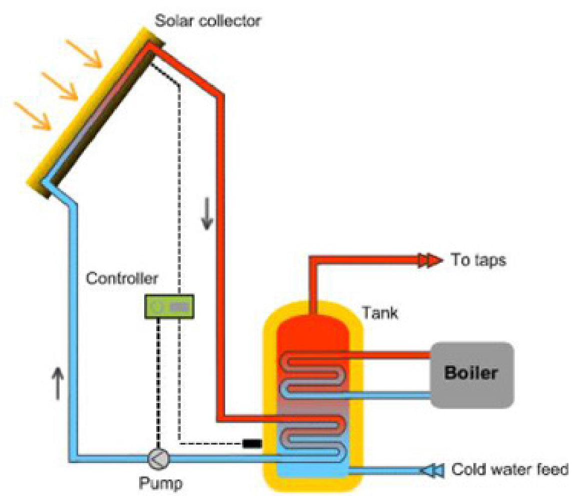


Figure 11 Evacuated Tubes Solar Collector System [11]

Solar water heater was sized for a five person house, with an estimated consumption of 50 liter per person per day. A 400 liter storage tank was chosen after utilizing graph of hot water consumption and storage capacity in Figure 12. The size of this storage tank allows for features in the house such as dishwasher, washing machine, and children taking several showers during the day. Water conservation measures should be taken into account, such as low flow showers, to decrease amount of hot water demand. Size of storage tank would decrease accordingly for a smaller family.

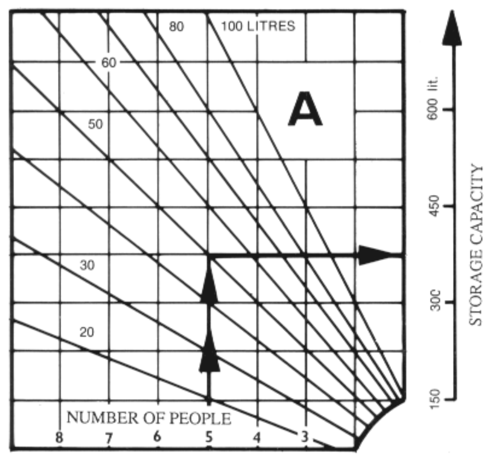


Figure 12 Hot water consumption and Storage capacity [20]

After sizing the storage tank capacity, the amount of evacuated tubes needed to heat 400 liters of water was analyzed using the chart in Figure 13below with an estimated amount of solar insolation of 1400 hours. According to this graph, 40 evacuated tubes are needed to meet hot water demand. Similar to PV panels, solar collector must be tilted at latitude angle of due south for maximum absorption of solar radiation.

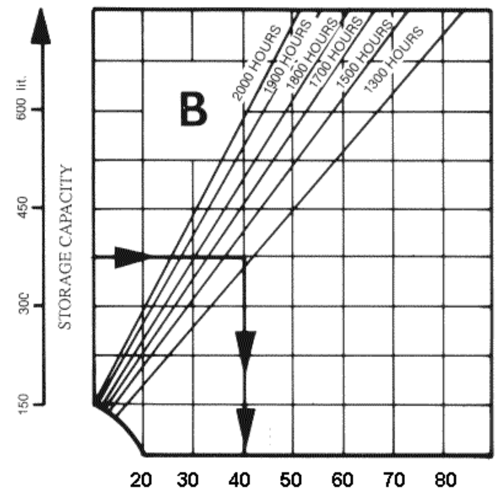


Figure 13 Solar Insolation [20]

To examine size of evacuated tube solar collector system, *Thermo Technologies* solar collectors were evaluated. Their solar collector product, called Mazdon collector, comes in packages of 20 or 30 tube manifolds. According to previous sizing, Turbine House requires two Mazdon collector 20 tube manifolds. The sizing and specification for Mazdon 20 is summarized in the table below:

System	**Mazdon 20**
Number of Tubes	20
Dimensions (W x L x D)	1.5m x 2m x 0.16m
Weight (Empty)	135 lbs.
Manifold's Capacity	0.12 US Gallons

Figure 14 Mazdon Collector Dimensions [20]

Total area of 40 evacuated tube solar collectors is 6 m^2, located in the same surface as the PV panels. The storage tank with heat exchanger will be located at the top of the Turbine House, below tilted solar roof.

4.2 Passive Solar Heating

Passive solar heating is the “absorption of solar energy directly into a building to reduce the energy required for heating the habitable spaces, also called space heating.” [1] According to U.S. Department of Energy, a typical family spends 40 to 60% or more of its annual utility budget on heating and cooling. Making use of passive heating through glazing, insulation and thermal mass, among other techniques, can significantly reduce space heating consumption. The ultimate goal of the Passive House standard is to carefully design a building that utilizes passive solar heating to minimize heating and cooling consumption, and even eliminate the need for mechanical heating and cooling. Passive Houses are expected to obtain 40% of space heating demand from solar gains. [25]

The strategy to optimize passive solar heating in the Turbine House is to "maximize solar heat gain in winter and minimize it in summer.” [20] To accomplish this, heating losses in the Turbine House must be kept down by employing an airtight and well insulated building envelope. The Turbine House will be facing south to optimize solar gain during winter caused by solar position, as shown in Figure 15.

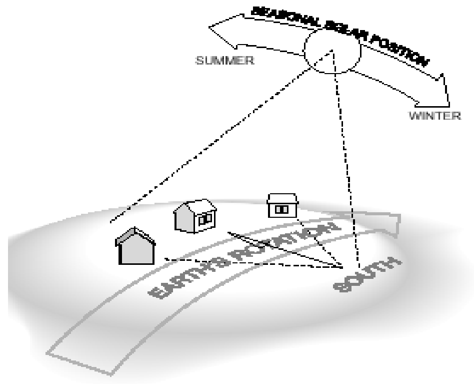


Figure 15 Seasonal Solar Position [18]

All the glazing and main living rooms will be concentrated on the south while little-used rooms such as bathrooms will be located in the north side. Refer to Figure 16 for floor plan options for the Turbine House.

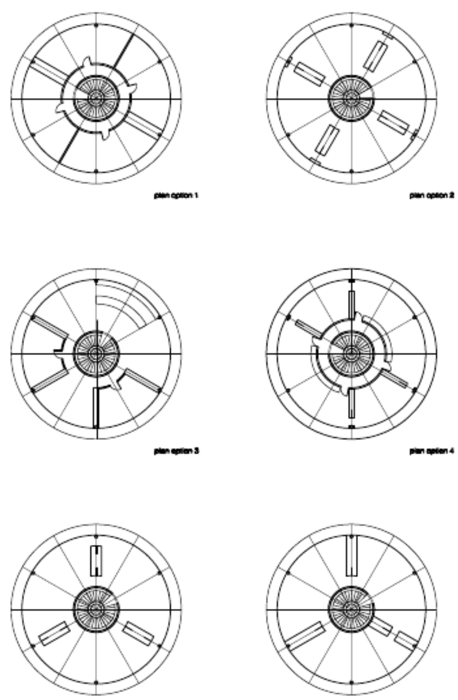


Figure 16 Floor plans options of the Turbine House

Another aspect that will be implemented in the Turbine House is daylighting, or "the use of windows and skylights to bring sunlight" into the house, to avoid electricity consumption from artificial lighting. [19] If artificial lighting is to be used, it must be used efficiently and turned off when natural light is available.

Additionally, overshading from other buildings or trees should be avoided so that the building can benefit from mid-winter sun. Overheating during the summer should also be avoided, due to excessive glazing. Thermal mass must be implemented if the façade consists of more than 7 percent of glazing.

The design of a house that utilizes passive solar heating efficiently is very challenging, and hard to adapt to different site locations. The Turbine House circular design provides the benefit of increasing adaptability to different site locations by just orienting PV panels and glazing side of the house to the south.

5.0 Solar Photovoltaic Energy

Photovoltaics is the conversion of solar energy directly into electricity in a solid state device, such as solar photovoltaic panels. Solar photovoltaic panels are being implemented in the tilted roof of the Turbine House. The tilted roof is angled according to site location for better efficiency and will be facing within 15^o of due south. This angle is equal to the latitude of the site. Optimally, the panel would be tilted an additional 15^o in the winter, and tilted less an additional 15^o in the summer. [22]

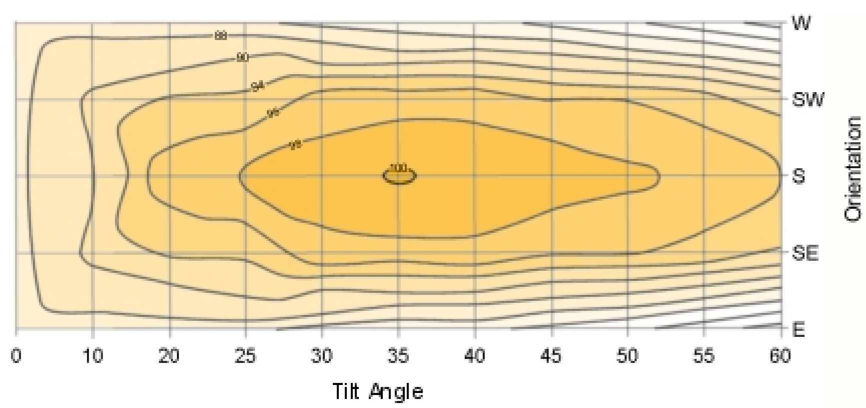


Figure 17 Approximate power produced with deviation from optimum tilt and directional angle [23]

Equally as important as the tilt and direction angles is the necessity to eliminate any shading effects on the entirety of the photovoltaic panel. The cells in a photovoltaic panel are connected to each other in a series configuration. Partial or complete shading of even one cell can significantly reduce the power output of the entire panel. For this reason, PV panels will be installed with 0^o from surface of tilted roof. This allows for higher surface area coverage, and higher power generation.

The total area of the tilted circular roof is 101 m², with diameter of 11.35 m. Since the tilted roof has a circular shape, and the silicon solar panels installed on the roof have a rectangular shape, several solar panel configurations were analyzed to obtain optimal power production. The one that implemented smaller solar panels with high efficiencies that will cover most surface area was chosen. This configuration, shown in Figure 18, consists of 77 solar panels that are 1 m² each. Surface area covered by PV panels is approximately 15% more compared to configuration of 4 m² PV panels.

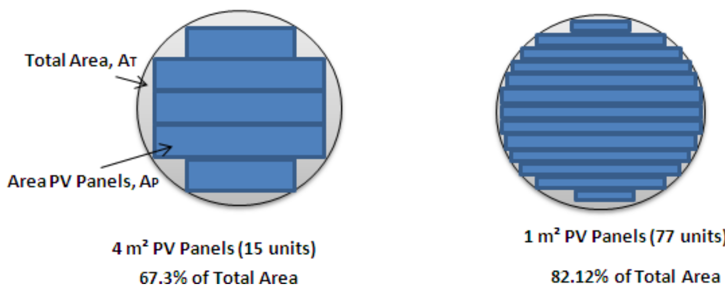


Figure 18 Solar Photovoltaic Panel configurations

For sizing purposes, the power generated by silicon solar photovoltaic panel was approximated, using theoretical values for a PV panel which were also compared to power values provided by PV panel manufacturer. Daily average full sunlight hours were approximated to be 5.5 hours, but this value is subject to change depending on site location and weather conditions. PV panel efficiency was estimated to be 16%, since the efficiency range for multicrystalline solar panels is typically 12-18%.

According to Boyle, peak power silicon PV cell voltage is 0.5 V, and maximum current in full sunlight (1 kW/m^2 at 25^oC) is 3A. The maximum power output, according to Equation (7) is 0.150 kW/m^2.

$$Power = Voltage \times Current \tag{7}$$

If 83 solar PV panels of $1m^2$ area are installed, the maximum power output would be **3710kWh/year**, taking into account efficiency and sun hours previously mentioned.

Compared to manufactured silicon PV panels, such as Kyocera modules, power generated by solar panels is rated at $0.108kWh/m^2$. For rated efficiency of 16-18%, and same full sunlight hours, their total power output would be **2994kWh/year**. In operation, however, the power output reported by the manufacturer will be higher than that of the panel or cell in operation.

6. Geothermal Heat Pump

Geothermal heat pump, or ground source heat pump (GSHP), transforms Earth Energy into useful energy to heat and cool buildings. [20] Earth energy is available on-site, and in massive quantities, given that 46% of sun's energy is absorbed by the earth as shown in Figure 19.

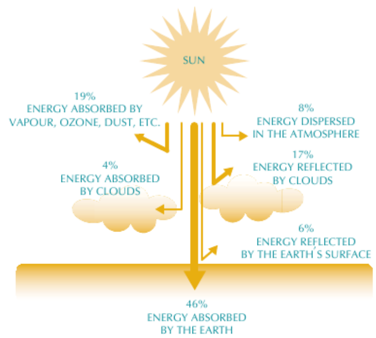


Figure 19 Solar Energy Distribution [24]

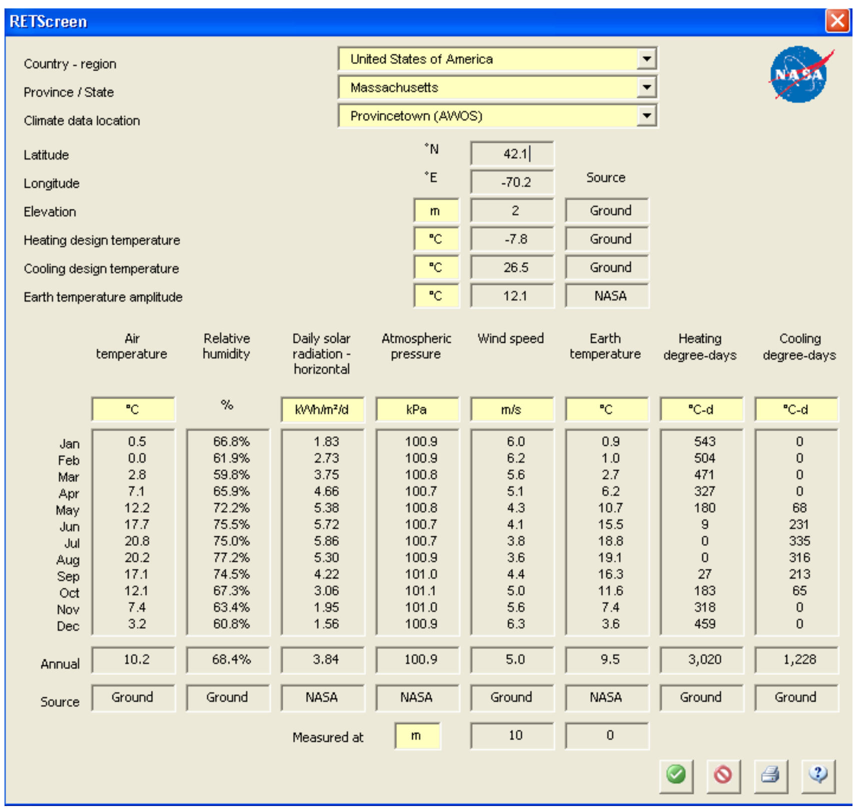
A ground source heat pump provides low temperature heat by utilizing the ground as a heat source and can provide cooling by utilizing the ground as a heat sink. Some ground source heat pumps can also provide domestic hot water by applying a desuperheater. A desuperheater will be included in the ground source heat pump of the turbine house to serve as a backup option for domestic heat water. The type of heat pump that will be utilized in the Turbine House is a water-to-air heat pump, since it is one of the most common small scale heat pumps utilized for residences.

Typically, GSHP's efficiency ranges from 200-500 percent over a season. On average, for every kilowatt (kW) of electricity used by the GSHP, 3 kW are drawn from the ground. For the Turbine House, a ground source heat pump of 1.3 kW was chosen as heat source since the maximum heat demand allowed is 12 W/m^2, or 1.3kW. The maximum heat demand required for the Turbine House is higher than that required by the Passive House standard, to adapt to extreme weather in the United States compared to weather in Germany. [8] Heat pumps typically range from 3.5 to 35 kW in cooling capacity, but this one was chosen to be smaller due to low demand of space heating.

Sizing of geothermal heat pump is highly dependent on site location. For this reason, RETScreen International Ground-Source Heat Pump Project Model was utilized to evaluate energy production for heating and/or cooling of residential, commercial, institutional and industrial buildings. Climate conditions at Cape Cod, Massachusetts were taken into account for these calculations.

7. Case Study: Turbine House at Cape Cod, Massachusetts

As previously mentioned, Cape Cod, Massachusetts, was chosen to perform energy analysis of the Turbine House. Wind energy, solar photovoltaic energy, solar thermal energy, and geothermal energy previously considered were analyzed for site specific conditions. Average annual wind speed, according to U.S. Department of Energy, is 6.4 m/s, for wind power class 5. For similar constraints specified in Figure 20, power provided annually by wind turbine is **13466.5kWh/year**; moreover, power output for the wind turbine is **1.7kW** at 6.4 m/s.



	Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
	°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
Jan	0.5	66.8%	1.83	100.9	6.0	0.9	543	0
Feb	0.0	61.9%	2.73	100.9	6.2	1.0	504	0
Mar	2.8	59.8%	3.75	100.8	5.6	2.7	471	0
Apr	7.1	65.9%	4.66	100.7	5.1	6.2	327	0
May	12.2	72.2%	5.38	100.8	4.3	10.7	180	68
Jun	17.7	75.5%	5.72	100.7	4.1	15.5	9	231
Jul	20.8	75.0%	5.86	100.7	3.8	18.8	0	335
Aug	20.2	77.2%	5.30	100.9	3.6	19.1	0	316
Sep	17.1	74.5%	4.22	101.0	4.4	16.3	27	213
Oct	12.1	67.3%	3.06	101.1	5.0	11.6	183	65
Nov	7.4	63.4%	1.95	101.0	5.6	7.4	318	0
Dec	3.2	60.8%	1.56	100.9	6.3	3.6	459	0
Annual	10.2	68.4%	3.84	100.9	5.0	9.5	3,020	1,228
Source	Ground	Ground	NASA	NASA	Ground	NASA	Ground	Ground

Figure 20 RETScreen Climate Data for Provincetown, Massachusetts [21]

Solar Photovoltaic Panels installed in Turbine House at Cape Cod, Massachusetts, should be tilted approximately 42 degrees facing due south to obtain maximum solar gain, since latitude of Cape Cod is 42.1 degrees, as shown in Figure 20. Power provided annually by solar photovoltaic panels, for an average of 5.5 hours of full sunlight per day, and 1m² PV panels, is **2993.9 kWh/year**. PV panel roof arrangement has a rated power output of **8.9kW**.

Active solar thermal energy will also be installed in the roof occupying 6m², and providing up to 3kW of power. This will provide annual domestic water heater needed. Passive solar thermal energy maximizes solar gain without overheating. Therefore, glazing side of the house will be facing south, but balanced with thermal mass in north side of Turbine House and inside the house (e.g. walls, floor) to avoid overheating during the summer.

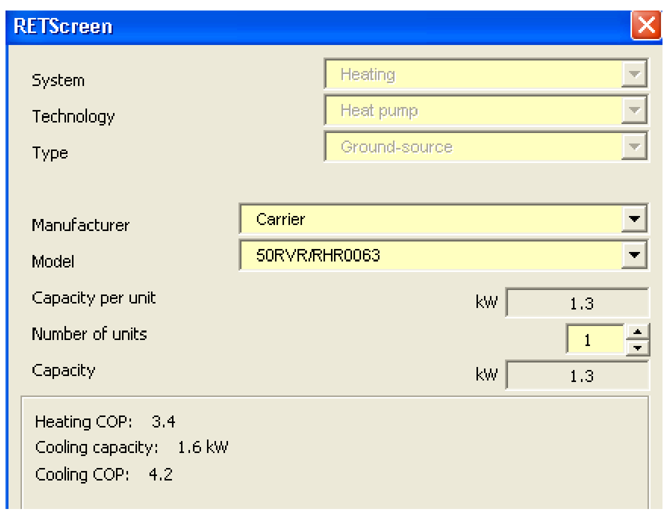


Figure 21 Ground Heat Exchanger Manufacturer Information

Geothermal heat pump sizing calculations were executed in RETScreen software. Manufacturer chosen was Carrier, and size of the geothermal heat pump is 1.3kW, with heating COP of 3.4 and cooling COP of 4.2, also refer to Figure 21. The average load for each heating and cooling was assumed to be 0.5kW. This provided, for all different types of soils, required sizing measurements of minimum land area and borehole length (e.g. Vertical closed-loop) and minimum land area, loop length, and trench length (e.g. Horizontal closed-look). These are summarized in Table 4.

	Vertical Closed Loop		Horizontal Closed Loop		
Type of Soil	Min. Land Area	Borehole Length	Min. Land Area	Loop Length	Trench Length
Light Soil - Damp	29	50	77	63	32
Light Soil - dry	29	110	169	135	67
Heavy Soil - damp	29	36	56	46	23
Heavy Soil - dry	29	50	77	63	32
Light rock	29	23	36	29	15
Heavy Rock	29	18	28	23	12
Permafrost - light	29	35	54	44	22
Permafrost - dense	29	26	40	32	16

Table 4 1kW Ground Heat Exchanger at Cape Cod, Massachusetts

Most of these arrangements of vertical closed-loop and horizontal closed-loop are extremely site dependent since the type of soil is an important factor in the sizing, and it is not known. Light soil (dry) is least advantageous, since much more area is needed to obtain same amount of heating and cooling. In fact, if the land area is less than 100m², the horizontal closed-loop heat pump is not feasible because it requires 169 m² of minimum land area. RETScreen is a useful tool, but further details about type of soil are needed to obtain more specific results.

8. Conclusion

As a result, the Passive House standard was chosen for its ultra-low primary energy annual consumption of 120 kWh/m²year. The treated floor area dimensions of the Turbine House were adjusted from 632m² for the preliminary design to 111m² for the final design. The maximum annual energy consumption from the Turbine House, including domestic hot water and space heating, is 13304.8 kWh/year. To meet all energy needs, wind energy, solar photovoltaic energy, solar thermal energy and geothermal energy must provide sufficient.

7.1 Wind Energy

Cross sectional area of wind turbine is 26.5m², with rated power output of 1.7kW at 6.4m/s wind speed. At Cape Cod, Massachusetts, this wind turbine will provide 13466.5kWh/year, which represents 69% of total renewable energy provided to the house.

7.2 Solar Photovoltaic Energy

An arrangement of 77 PV panels, 1m² each, installed on tilted roof are rated at 8.9kW and expected to provide **2993.9kWh/year** to the Turbine House, which represents 16% of renewable energy provided. For the Turbine House in Cape Cod, Massachusetts, roof will be tilted 42 degrees and facing south for optimal solar gain.

7.3 Solar Thermal Energy

To obtain passive solar thermal energy, building façade with most glazing will be facing south and all the widely used rooms (e.g. living room) also facing south. The other half of the building will consist of thermal mass, facing north, with most of the smaller rooms (e.g. bathrooms). Passive solar thermal energy will allow the Turbine House to achieve ultra-low annual energy consumption by reducing space heating consumption. Active solar thermal energy consists of 40 evacuated tubes with storage tank and heat exchanger that will take up to 6m² area from tilted roof and will provide domestic water heating, an average of 3000kWh/year. This represents 15% of total renewable energy provided to the Turbine House.

7.4 Geothermal Energy

Since geothermal energy cannot be implemented, or is not cost-effective to be implemented in all locations, it was not included in the total expected renewable energies. For Cape Cod, Massachusetts, geothermal heat pump of 1.3kW will be installed, depending on type of soil. It will serve as backup for space heating and domestic water heating.

Energy generated by the combination of renewable energies implemented meet annual energy consumption requirements in the Turbine House, resulting in a net-zero energy house.

9. Summary

Renewable energies, or energy flows which are replenished at the same rate as they are used, are needed to reduce carbon emissions in the range of 60-80% by the end of the twenty-first century. [1] Energy used in houses nationwide contributes to 16% of generated greenhouse gas emissions. [3] This large percentage of greenhouse emissions could be reduced by designing and developing energy efficient houses, or net-zero energy houses, such as the Turbine House.

The main goal of this project is to perform sizing calculations to adjust preliminary design dimensions for both renewable energy technologies and treated floor area to obtain a net-zero energy house. The Turbine House combines wind energy, solar photovoltaic energy, solar thermal energy, and geothermal energy to offer a fully integrated sustainable solution for off-the-grid living. Features of the passive house standard, which is a rigorous, strict and voluntary energy performance standard first developed in Germany by Wolfgang Feist, will be implemented in the Turbine House. According to Passive House institute, a passive house must maintain primary energy consumption under 120kWh/m^{2}year. This is achieved by reducing 90% of space heating energy consumption. In typical US households space heating and cooling contributes to almost 50% of total energy consumption. [11] According to Passive House standard, space heating consumption must be kept under 15kWh/m^{2}year. This means that the Turbine House must not consume more than 13304.8 kWh/year of primary energy, and not more than 1663.1 kWh/year of space heating. For the Turbine

House, peak space heating demand should be lower than 12 W/ m², or 1.3kW. This required amount is different than that required in German Passive Houses, which is 10 W/ m² to adapt the Passive House standard to U.S. extreme weather conditions.

The Turbine House will also utilize triple glazed, low-e windows, superframe, airtight and highly insulated building envelope to reduce heat loss. The side of the Turbine House facing south will contain most of the glazing, to maximize solar gain during winter. Rooms most often used (e.g. living room) should face south, while other rooms (e.g. bathrooms) should face north. Daylighting, also called natural lighting, and natural ventilation will be utilized in the Turbine House to reduce its energy consumptions.

Wind Energy is the conversion of kinetic energy from wind to electricity. It will be generated from a Darrieus type vertical-axis wind turbine, located at the top of the house. One of the benefits of this type of wind turbine is its ability to receive incoming wind from different directions, without affecting its performance. The converging section that precedes the turbine is expected to increase its efficiency, and provide higher rated power output. This type of renewable energy technology will provide 69 percent of the total renewable energy provided to the Turbine House.

Solar photovoltaic energy is the conversion of solar energy directly to electricity. Energy generated by photovoltaic panels is directly related to the cross sectional area of panel, solar capacity for specific location, and tilt angle of panel. Higher cross sectional areas provide higher power output, as well as higher solar capacity measured in average sun hours for site location. The tilt angle of the panel must be optimized based on site location. In order to maximize power production, the solar panel should be tilted at an angle approximately equal to the latitude of the site and facing within 15° of due south. Optimally, the panel would be tilted an additional 15° in the winter, and tilted less and additional 15° in the summer. This type of energy will be implemented in the tilted roof of the Turbine House. Solar PV energy will provide 16 percent of total renewable energy provided to the Turbine House.

Solar thermal energy is referred to the solar radiation that is converted into heating energy. Two different approaches will be implemented in the Turbine House: passive solar heating and active solar heating. Knowledge of solar geometry, window technology and seasonal temperatures are crucial factors for integrating passive solar design. Passive solar heating will be implemented with Passive House standard features such as increased glazing facing south. Active solar heating will be implemented in the Turbine House through evacuated tube solar collectors. These were chosen for their higher efficiency compared to flat plate solar collectors, even though flat plate collectors are more common. For a five person house, forty evacuated tubes are required to provide enough domestic heat water. These will be located on the tilted roof of the Turbine House, and connected to a heat exchanger and storage tank that will distribute hot water to the house. Solar thermal energy will account for 15 percent of the total renewable energy provided to the house.

Geothermal Heat Pump (GHP) system, or earth coupled closed loop heat pump system, provides space heating and cooling to the building, utilizing constant temperature of the earth. It acts as a heat source for heating days and heat sink for cooling days. Vertical closed loop installations are highly dependent on geothermal temperature gradient, while horizontal closed loop installations are influenced by solar radiation due to their superficial placement. [27] If drilling is permitted and cost effective at site location, vertical closed loop installations will be preferred. Otherwise, horizontal closed loop installations are chosen, and land area becomes a crucial factor. For both installations, type of soil is also important, since light soil has higher thermal conductivity than hard rock. This system is very efficient in humid areas to control moisture in the building. A desuperheater can be added to the system to also provide domestic hot water (DHW). RETScreen software, Canadian software sponsored by Minister of Natural Resources Canada, that utilizes climate data from NASA, was utilized to analyze site specific conditions and perform sizing calculations for geothermal heat pump. Average load taken from passive house standard numbers. Maximum was to be 1.3 kW, part of which is supplied by heat recovery system and other part supplied by geothermal heat pump when type of soil allows it to be installed.

Cape Cod, Massachusetts, was chosen as site with abundant renewable energy resources. Environmental, architectural and system variables were taken into account for site specific energy analysis.

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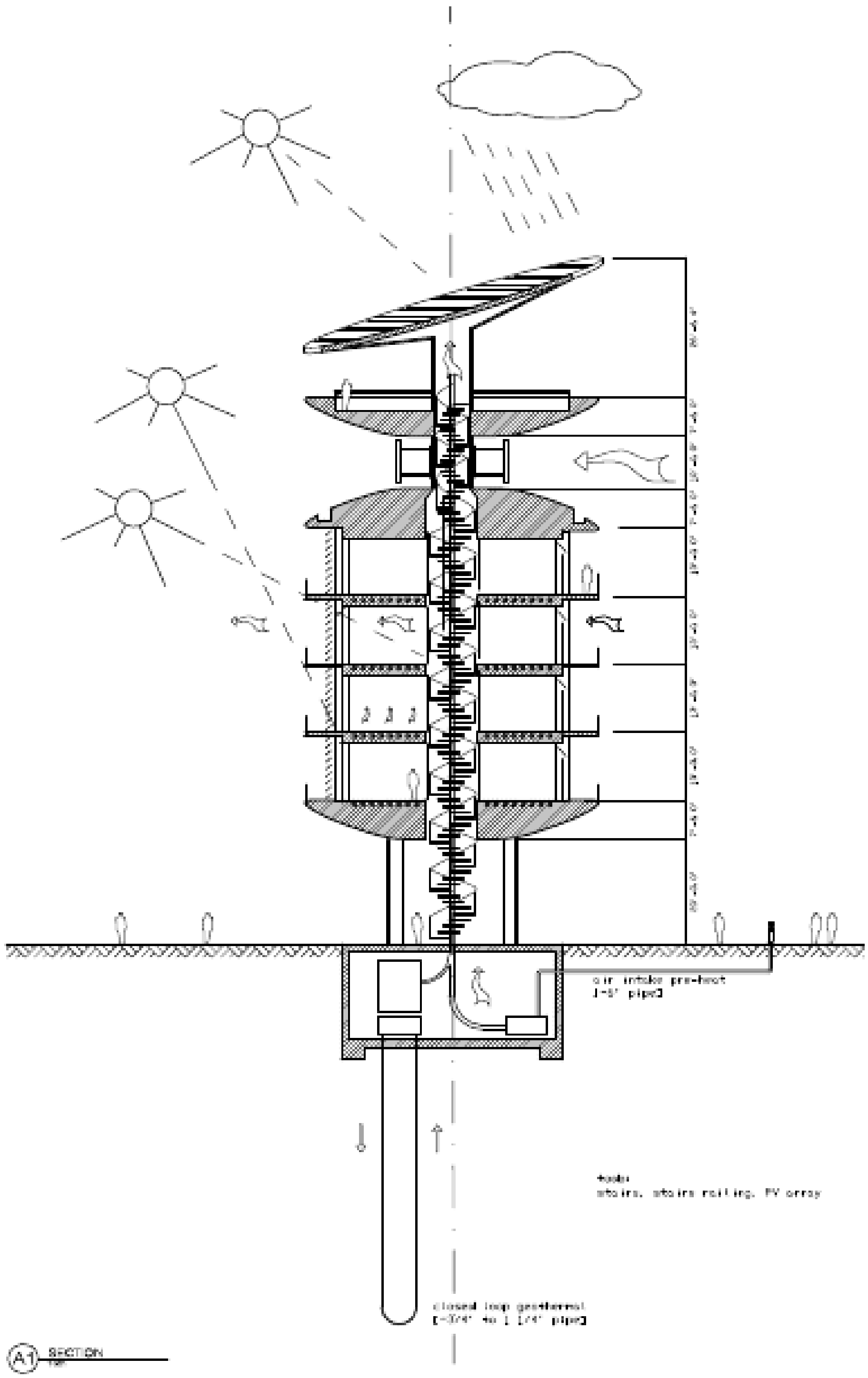
APPENDIX

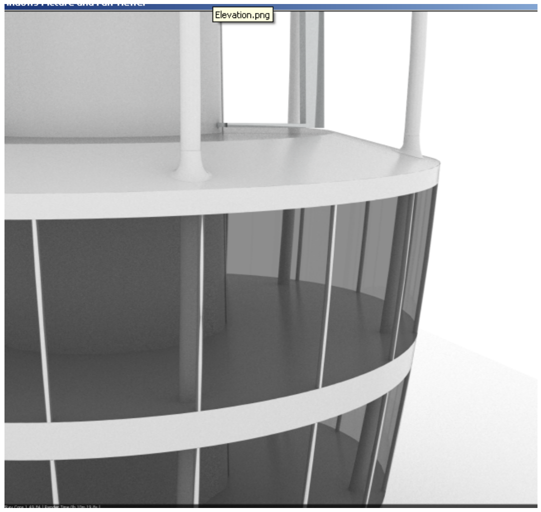
B. Turbine House design
    A-1 Preliminary Design
    A-2 Final Design
C. Energy Analysis Calculations
    B-1 Turbine House, Passive House and Typical US Household Comparison
    B-2 Estimated Energy Consumption per Year
    B-3 Solar Photovoltaic Energy Calculations
    B-4 Wind Energy Calculations
    B-5 Wind Turbine Power Curve
    B-6 Climate Conditions, Cape Cod, Massachusetts
    B-7 Geothermal Heat Pump Calculations, Cape Cod, Massachusetts

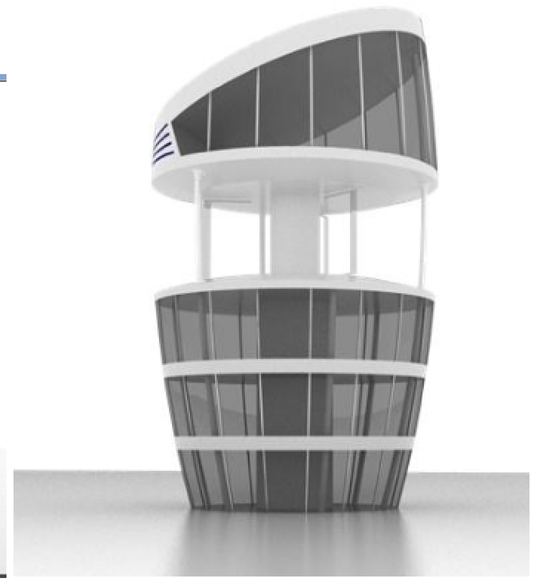
A. Turbine House Design

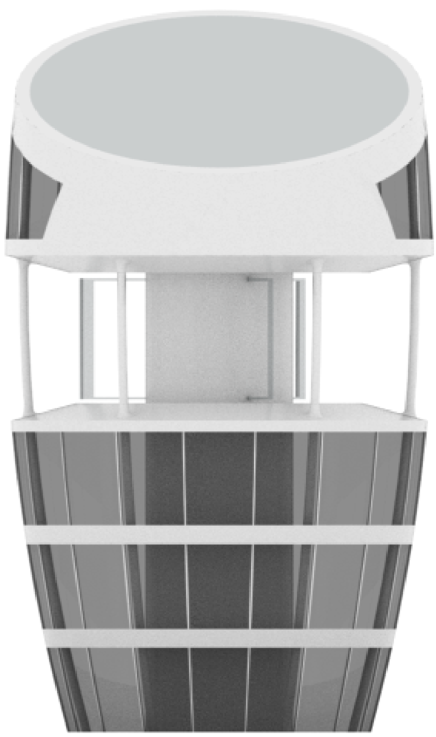
A-1 Preliminary Design

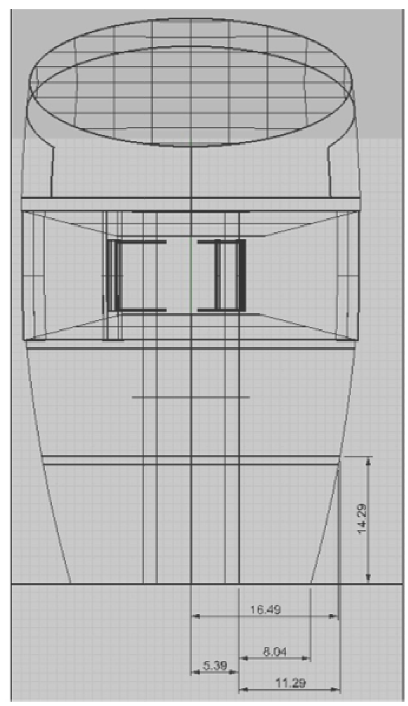


A-2 Final Design









B. Energy Analysis Calculations

B-1 Turbine House, Passive House and Typical US Household Comparison

Turbine House

Summary of Energy Analysis

		Average US Household	Passive House Standard	Turbine House
Treated Floor Area		201.8 m^2	20-50 m^2/person	110.9 m^2 (3-5 persons)
Renewable Energy				
	Wind Power	0	0	1.7 kW (at 6.4m/s)
	Solar Photovoltaic Energy	0	0	8.9 kW (77, 1m^2 PV Panels)
	Solar Thermal Energy - Solar Collector	0	0	3000.0 kWh/year
	Solar Thermal Energy - Passive Heating	0	< 6 kWh/m^2year	6.0 kWh/m^2year
	Geothermal Heat Pump	0	0	1.0 kW
Primary Energy Consumed				
	Space Heating, Natural Gas	68.8 kWh/m^2year	< 15 kWh/m^2year	15 kWh/m^2year
	Air Conditioning	17.2 kWh/m^2year	< 15 kWh/m^2year	15 kWh/m^2year
	Domestic Water Heating, Natural Gas	32.3 kWh/m^2year	< 33 kWh/m^2year	33 kWh/m^2year
	Electrical Appliances (incl. lighting, refrigeration, cooking, washing, etc.)	36.3 kWh/m^2year	< 33 kWh/m^2year	33 kWh/m^2year
Specific Primary Energy consumption		**168.5 kWh/m^2**	**< 120 kWh/m^2year**	**120.0 kWh/m^2year**

B-2 Estimated Energy Consumption per Year

Turbine House- Estimated Energy Consumption per Year

Treated Floor Area		110.9 m^2	(3-5 persons)
Renewable Energy			
	Wind Power	13466.5 kWh/year	69.19963 %
	Solar Photovoltaic Energy	2993.9 kWh/year	15.3844 %
	Solar Thermal Energy - Solar Collector	3000.0 kWh/year	15.41597 %
Total Renewable Energy		**19460.3 kWh/year**	
Primary Energy Consumed			
	Space Heating, Natural Gas	1663.1 kWh/year	
	Air Conditioning	1663.1 kWh/year	
	Domestic Water Heating, Natural Gas	3658.8 kWh/year	
	Electrical Appliances (incl. lighting,	3658.8 kWh/year	
Specific Primary Energy consumption		13304.8 kWh/year	

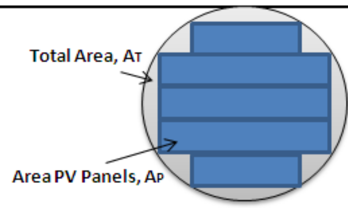
Natural gas, 1m^3=Electricity, 10kWh

B-3 Solar Photovoltaic Energy Calculations

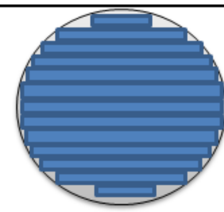
Turbine House

Active Solar Energy

Solar Photovoltaic Panels



4 m² PV Panels (17 units)
67.3% of Total Area



1 m² PV Panels (83 units)
82.12% of Total Area

PHOTOVOLTAIC PANEL Constraints				
Total Area, A_T	1089 ft²	101 m²		
Diameter Solar Panel	37.24 ft	11.35 m		
Full Sunlight Hours/day	5.5 h/day	5.5 h/day		
Full Sunlight Hours/year	2008 h/year	2008 h/year		
PV Efficiency	0.16	0.16		
SILICON PV MODULES (Theoretical Values)			**Solar Power**	
Typical Silicon PV Cell Area	0.11 ft²	0.01 m²		
Peak Power Silicon PV Cell Voltage	0.5 V	0.5 V		
Maximum Current in full sunlight (1 kW/m² at 25°C)	3 A	3 A		
Average Power per Silicon PV Cell	0.014 kW/ft²	0.150 kW/m²		
Average PV Module Area	3.88 ft²	0.36 m²		
Area PV Panels, A_P (1m², 77 units)	829 ft²	77 m²	3710	kWh/year
Area PV Panels, A_P (4m², 15 units)	646 ft²	60 m²	2891	kWh/year
KYOCERA PV MODULES			**Solar Power**	
PV Panel Peak Power	0.010 kW/ft²	0.108 kW/m²		
PV Panel Efficiency	0.180	0.180		
PV Panel Installed Capacity, 1m²		8.285 kW		
PV Panel Installed Capacity, 4m²		6.456 kW		
Area PV Panels, AP (1m², 77 units)	829 ft²	77 m²	2994	kWh/year
Area PV Panels, AP (4m², 15 units)	646 ft²	60 m²	2333	kWh/year

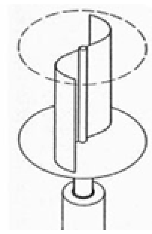
B-4 Wind Energy Calculations

Turbine House

Vertical Axis Wind Turbine (VAWT)


[1]

Darrieus Wind Turbine
Cut-in Wind Speed: 4 m/s
Efficiency: 0.4

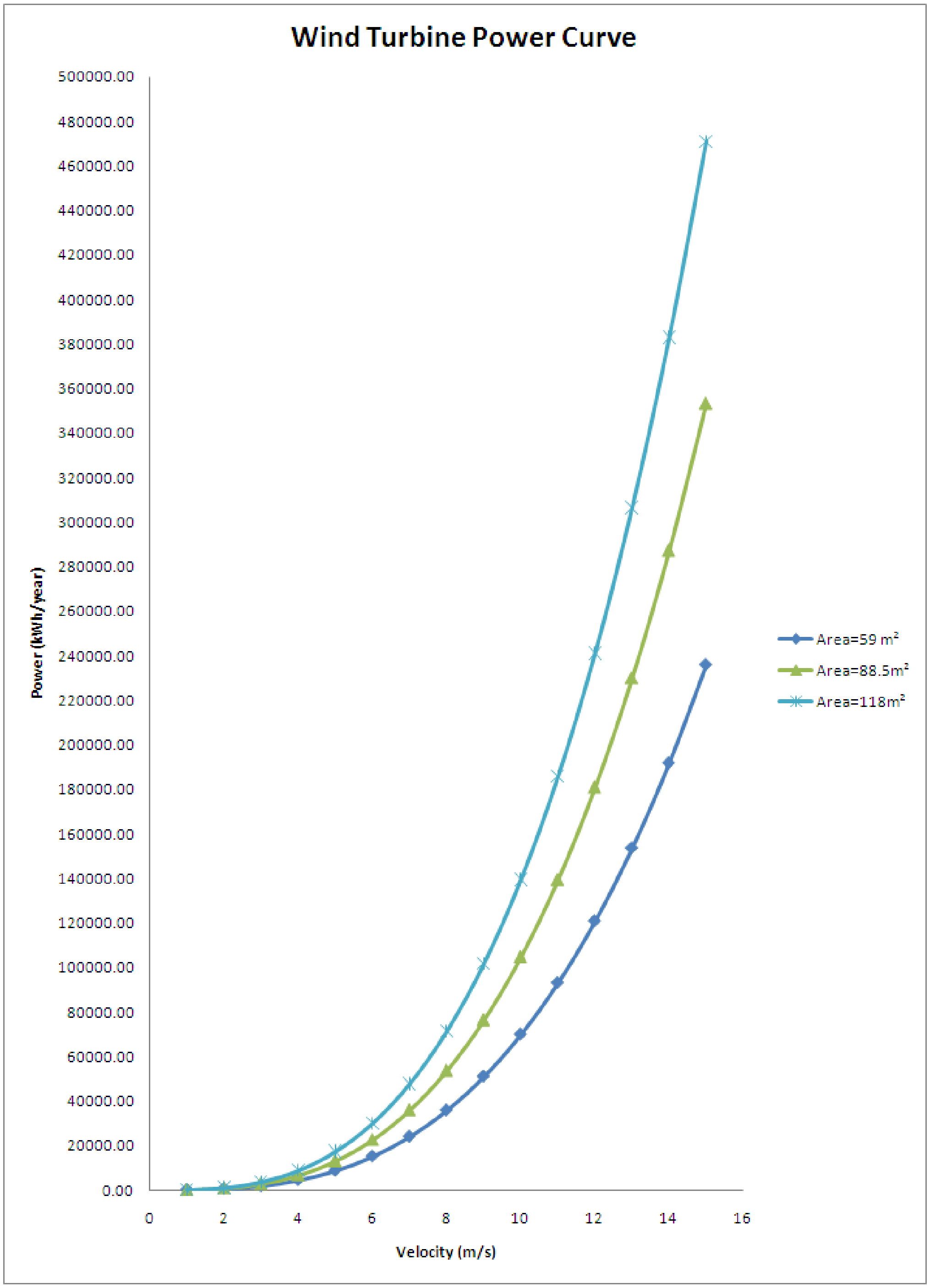

[2]

Savonius Wind Turbine
Cut-in Wind Speed: 1 m/s
Efficiency: 0.3

WIND TURBINE CONSTRAINTS				
Wind Capacity	0.9	0.9		
Hours/year	8760 h/year	8760 h/year		
Air density	0.077 lb/ft³	1.23 kg/m³		
Wind Turbine Area	285 ft²	26.49 m²		
DARRIEUS WIND TURBINE				
Efficiency	0.4	0.4		
Wind Power Resource (DOE) at 10m			**Rated Power**	**Wind Power**
Class 1	14.43 ft/s	4.4 m/s	0.6 kW	4375.9 kWh/year
Class 2	16.73 ft/s	5.1 m/s	0.9 kW	6814.4 kWh/year
Class 3	18.37 ft/s	5.6 m/s	1.1 kW	9021.5 kWh/year
Class 4	19.68 ft/s	6 m/s	1.4 kW	11096.0 kWh/year
Class 5	20.99 ft/s	6.4 m/s	1.7 kW	13466.5 kWh/year
Class 6	22.96 ft/s	7 m/s	2.2 kW	17620.1 kWh/year
Class 7	30.83 ft/s	9.4 m/s	5.4 kW	42667.6 kWh/year
SAVONIUS WIND TURBINE				
Efficiency	0.3	0.3		
Wind Power Resource (DOE)			**Rated Power**	**Wind Power**
Class 1	14.43 ft/s	4.4 m/s	0.4 kW	3282.0 kWh/year
Class 2	16.73 ft/s	5.1 m/s	0.6 kW	5110.8 kWh/year
Class 3	18.37 ft/s	5.6 m/s	0.9 kW	6766.1 kWh/year
Class 4	19.68 ft/s	6 m/s	1.1 kW	8322.0 kWh/year
Class 5	20.99 ft/s	6.4 m/s	1.3 kW	10099.9 kWh/year
Class 6	22.96 ft/s	7 m/s	1.7 kW	13215.1 kWh/year
Class 7	30.83 ft/s	9.4 m/s	4.1 kW	32000.7 kWh/year

[1] http://www.soue.org.uk/souenews/issue7/tidal1.jpg
[2] http://www.reuk.co.uk/print.php?article=Savonius-Wind-Turbines.htm

B-5 Wind Turbine Power Curve



B-6 Climate Conditions, Cape Cod, Massachusetts

Turbine House

Cape Cod, Massachusetts

Site Conditions

	Unit	Climate data location	Project location
Latitude	°N	42.1	42.1
Longitude	°E	-70.2	-70.2
Elevation	m	2	2
Heating design temperature	°C	-7.8	
Cooling design temperature	°C	26.5	
Earth temperature amplitude	°C	12.1	

Month		Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
		°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January		0.5	66.8%	1.83	100.9	6.0	0.9	543	0
February		0.0	61.9%	2.73	100.9	6.2	1.0	504	0
March		2.8	59.8%	3.75	100.8	5.6	2.7	471	0
April		7.1	65.9%	4.66	100.7	5.1	6.2	327	0
May		12.2	72.2%	5.38	100.8	4.3	10.7	180	68
June		17.7	75.5%	5.72	100.7	4.1	15.5	9	231
July		20.8	75.0%	5.86	100.7	3.8	18.8	0	335
August		20.2	77.2%	5.30	100.9	3.6	19.1	0	316
September		17.1	74.5%	4.22	101.0	4.4	16.3	27	213
October		12.1	67.3%	3.06	101.1	5.0	11.6	183	65
November		7.4	63.4%	1.95	101.0	5.6	7.4	318	0
December		3.2	60.8%	1.56	100.9	6.3	3.6	459	0
Annual		10.2	68.4%	3.84	100.9	5.0	9.5	3,020	1,228
Measured at	m					10.0	0.0		

Source: RETScreen International

B-7 Geothermal Heat Pump Calculations, Cape Cod, Massachusetts

Turbine House

Cape Cod, Massachusetts

Ground Heat Exchanger

Manufacturer	Carrier			
Model	50RVR/RHR0153			
Heat pump	**Heating**		**Cooling**	
Capacity	3.1	kW	4.3	kW
Average load	1.5	kW	1.0	kW
Efficiency	High		High	
Coefficient of performance	4.0		5.5	
Layout	Standard		Standard	

	Vertical Closed Loop		Horizontal Closed Loop		
Type of Soil	Min. Land Area	Borehole Length	Min. Land Area	Loop Length	Trench Length
Light Soil - Damp	29	147	224	184	92
Light Soil - dry	88	326	486	398	199
Heavy Soil - damp	29	105	162	132	66
Heavy Soil - dry	29	147	224	184	92
Light rock	29	66	101	83	41
Heavy Rock	29	51	78	64	32
Permafrost - light	29	102	155	127	64
Permafrost - dense	29	73	112	92	46