Freshman Engineering Clinic II – Design for the Other 90%

# **Water Pumping Project – Developing MatLab Code**

**Objective**:

In this activity, you will develop Matlab Code for ‘sizing’ energy systems designed to pump drinking water for a small community in the developing world. The term ‘sizing’ refers to the process of determining the size and/or model number of system components and the numbers of these components. There are two types of systems that you will be sizing:

1. A stand-alone photovoltaic system with battery storage.
2. A fuel powered generating system.

For the stand alone photovoltaic system, you will need to identify a type of solar panel and the type of lead-acid storage battery. You will also determine how many of each are needed. For the fuel powered generator system, you will need to determine the type of generator required and the amount of fuel that will be consumed for water pumping.

**Overview:**

Your Matlab Code will consist of the 8 sections which appear below. You will code Sections 1, 2, 5, and 6 shown below, in **Bold** lettering:

1. **Establishing Site Parameters**
2. **Determining Daily Water Requirements**
3. Determining Daily Solar Insolation (Provided by Instructor)
4. Sizing the Solar Array (Provided by Instructor)
5. **Sizing the Battery Storage**
6. **Determining the Generator Power**
7. Calculating Costs (Provided by Instructor)
8. Displaying Results (Provided by Instructor)

The members of your team should divide the bolded sections above, so that each member works on code relating to their individual sections. The code for the non-bolded sections (Sections 3, 4, 7 and 8) is provided and should not be deleted or changed. In order for the code to work, each team member’s code must be combined at the end.

Students can code the sections independently, but the team must create one Matlab script into which all sections will be added together, sequentially – Section 1 followed by Section 2, then Section 3, etc. It is crucial that all team members use the same variable names. Variables that differ only by case (upper versus lower) will be interpreted as different. The variables used in the code developed by Instructors are shown in the Appendix.

Instructions are provided to help you develop with code. Sample data and results are provided, for each section, to help you test whether the code is functioning properly. Each section can be coded and tested independently, however, when all sections are complete they must be combined, sequentially, into one m-file. The sections are interdependent and it will not be possible to size systems for varying conditions unless all section (1 through 8) are combined, sequentially, into one m-file.

A flowchart for the sequence of each section is shown on the following page.























**Figure 1 - Flowchart for Matlab Code**

**Deliverables**

Each team will turn in one team memo with the following:

1. Matlab Code - Each student should work on 1 or more sections of the MatLab code. Once each section is complete, the sections should be combined to form one complete m-file. Identify which section of the code each student developed as a comment.
2. Monthly Energy Plots - Include the plots of monthly energy for various tilt angles as attachments to the memo. Discuss the effect varying tilt angle has on monthly energy.
3. Results tables - For each parameter varied (tilt angle, storage days, fuel costs, population, and location), include tables which summary the numbers of panels, numbers of batteries, solar energy system costs, generator costs, and time for the accumulated costs of the systems to become equal.
4. Discussion of the questions shown below.

**Questions**:

Once your code is working, you can investigate the effect of variations on the system sizing and economics. Discuss the following.

1. The solar energy system design was simplified for this activity. What other considerations should be addressed to help develop a more accurate model, particularly regarding the system costs?
2. The electric generator model was also simplified for this simulation. What factors should be included to develop a more accurate economic analysis of this system?
3. Change the value of Beta (the tilt angle of the solar panels). What impact does this have on the photovoltaic system size and cost?
4. Run the code with 1 and 2 storage days for the battery. How does the value of storage days affect the size and economics of the photovoltaic system?
5. Put in a different value for the unit cost of fuel. Discuss how this affects the time it takes for the accumulated costs of the two systems to become equal.
6. Run the code with a population of 100 and a population of 10,000. What is the effect of population on the size and economics of the systems?
7. Move the system to a latitude and longitude in another country (Not too far). How different are the systems?

**Instructions for Each Section:**

**General** – Throughout Code

The framework of the code that you are provided with contains instructions, comments, universal constants, and place holders for other quantities. In each section of the code, you will be required to:

* Establish values of parameters
* Create equations

Several calculations are simple unit conversions. One way to convert units is to reuse the same vector name in the conversion formula. For example, the equation ***L = 36*** can be used to represent the length of a pipe which is 36 inches long. The equation ***L = L / 12***, converts the length, in inches, to a length in feet – 3 feet in this example.

In addition to establishing quantities and writing equations, some sections, you require you to use conditional operations. Other sections will require commands such as min (to find the minimum of a vector), max (to find the maximum of a vectors), and ceil (to round off to the highest integer value), and similar operations. Section 8, involves creating a plot and a table of data.

As you develop your code, you should check to make sure that it is functioning properly. Sample data and calculations are provided in this document and in the powerpoint presentation. You can see the output of a calculation by leaving off the semicolon that is usually put at the end of the line. If your code results in an error or does not give the same results, you need to check it for errors.

Periodically, select your entire code, copy it, and paste it into a word document that you save. Save the Matlab file as well. It is also good to have several backups. Remember: **Save Early and Save Often**

**Top of Script** – Title, Group Members, Description, Date of Last Revision, Clear Memory, Close Figures

It is a good practice to include comments, at the top of the script, that identify a title, author(s), brief description, and the date of the last revision. To ensure the accuracy of calculations, it is also helpful to clear the memory – at least of the variables used by the code. The command to clear all variables is ***clear all.*** Since you will be generating plots, it is also helpful to close previous figures using the ***close all*** command.

**Section 1** - Establish Site Parameters

In this section, you will select a location for your solar water pumping project and establish constants specific to the location. Make sure that the location is in an underdeveloped part of the world. Use information from the location to create location specific quantities.

Parameters:

* **Latitude** and **Longitude** -Values of your site (in degrees) → Find this online (NOTE: Use negative numbers for latitudes in the Southern Hemisphere and for Longitudes East of the Prime Meridian)
* **Population** - Population of a small town/village at your site → Start with 5000. You will vary this after the code is working.
* **Water\_person** - Daily Water consumption per person in Liters or Gallons → Choose a value in liters or gallons based on information in online resources\*
* **h\_water** - Height (depth) of the water table in feet → Find this value online for you latitude/longitude. Use 100 feet if you can’t find any reference online.

\* Consult the following references:

1. <http://www.un.org/waterforlifedecade/pdf/human_right_to_water_and_sanitation_media_brief.pdf>

2. <https://hdr.undp.org/sites/default/files/reports/267/hdr06-complete.pdf>

3. <http://www.data360.org/dsg.aspx?Data_Set_Group_Id=757>

Imported Data:

* **Tamb** - 1 X 12 vector for the average daily ambient temperature in Fahrenheit →

First - Make a large matrix of monthly values of Tamb from all over the world. To do this, go to the NASA temperature database at <https://eosweb.larc.nasa.gov/sse/global/text/22yr_TSKIN>. Create an Excel file for this data. Make sure to include only one line of headers along with the data. Use the ‘text to columns’ feature under the ‘Data’ tab to get the data in separate columns.

Second - Use indexing to convert the large matrix into a one row matrix for the latitude and longitude of your site (NOTE: Use the Rounded Values). The latitude is in the first column of the matrix and the longitude is in the second column. You will need to using logical indexing based on these columns. For example, given X = [1,2,3,4,5; 1,3,5,7,9; 2,3,4,5,6], the command to get the row in which the first element is 1 and the second is 3, is as follows:

 y= X( (X(:,1) == 1 ) & ( X(:,2) == 3) , *startOutput* : *endOutput*  )

Third - Use indexing to make a 1 X 12 vector using the 3rd to 14th columns of the 1 X 15 length vector produced in the previous step. Let *startOutput* = 3 and *endOutput* = 14 or ‘end-1’.

Calculations

* **Latitude** and **Longitude -** Round these values to the nearest whole number.
* **Water\_total** - Total daily water consumption in Liters or Gallons → Use **Water\_person** and **Population**.
* **Water\_total** - Total daily water consumption in cubic meters → Convert units of **Water\_total**.
* **Q** - Daily Water flow rate in cubic meters per second → Use **Water\_total** and assume all water occurs in 6 hours a day.
* **h\_water** - Well depth in meters → Convert units of **h\_water** .
* **h\_pump** - Pump depth in meters → Add 5 meters of **h\_water**.

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**Sample Results - Section 1**

Input Values

Latitude = 18.24 degrees

Longitude=-66.36 degrees

Population= 5000

Water\_person=20 L

h\_water= 230 ft

Results

Tamb (Celsius)= 25.84 25.75 26.11 26.89 27.35 27.65 27.79 28.14 28.28 28.09 27.42 26.47

Water\_total= 100 m^3

Q= 0.0046 m^3/s

h\_pump=75.1 m

**Section 2** – Determine Daily Load

In this section, you will design a water pumping system that utilizes 4 inch diameter PVC pipes, connectors, and an elevated water tank. In this section you will not enter any constants or vectors because everyone is using the same types of pipes and connectors. You will, however, create equations for flow velocity, parameters associated with the flow of water, the total head, and the total energy needed to deliver the load. The physics behind these calculations is the principle of work. The work needed to lift the load (daily water) is its mass x gravitational acceleration x height. The calculation of height (head) needs to incorporate the distance from the pipe to storage tank in addition to major head losses due to the flow of water along the pipe and the minor head losses due to the pipe fittings. The major head losses are determined by first determining the type of flow (laminar or non-laminar) using the Reynold’s number. The Reynold’s number is used to determine a friction factor which is used in the head loss equation. We are using an approximation for Darcy Friction Factor developed by Papaevangelou, George & Evangelides, Chris & Tzimopoulos, Christos (2010). Minor head losses are determined using friction factors for the fittings in the minor head loss equation.

Calculations

* **D\_pipe** - Diameter of the water pipe in meters → Convert **D\_pipe** in inches to meters.
* **A\_pipe** - Cross sectional area of the water pipe in square meters → Use **D\_pipe.**
* **v** - Average velocity of water in pipe in meters per second a → $v=Q/A\\_pipe$
* **Re** - Reynolds number of water flowing in the pipe → $Re=v\*D\\_pipe/nu$
	+ Reynolds number is used to determine how a fluid will flow and can help predict how much energy is lost by the fluid as it flows through a pipe. Since we are determining the amount of energy needed to pump a given amount of liquid, the Reynolds number is a key part of that equation. Depending on how the fluid is flowing we must choose different friction factors as seen below.
* **f** - Friction factor → Use a conditional statement to set friction factor to zero if the flow velocity is zero. For non-zero flow rates, use an additional conditional statement to calculate the friction factor as follows:

For **Re** ≤ 2100 $f=64/Re$

For **Re** > 2100 $f=\frac{(0.2479-0.0000947(7-log\_{10} Re )^{4})}{(log\_{10} (\frac{\frac{epsilon}{D\\_pipe}}{3.615}+\frac{7.366}{Re^{0.9142}}) )^{2}}$(Source: Evangelides, Papaevangelou, Tzimopoulos, 2010)

Use an if, then, else statement here to use the right equation for the friction factor (f) above:
Example if then statement:

a = 100;
%check the boolean condition
 if a == 10
 % if condition is true then print the following
 fprintf('Value of a is 10\n' );
 elseif( a == 20 )
 % if else if condition is true
 fprintf('Value of a is 20\n' );
 elseif a == 30
 % if else if condition is true
 fprintf('Value of a is 30\n' );
 else
 % if none of the conditions is true '
 fprintf('None of the values are matching\n');
 fprintf('Exact value of a is: %d\n', a );
 end

When executed:

None of the values are matching
Exact value of a is: 100

In order to pump a certain amount of water, we must calculate how much energy is lost in pumping due to friction (head loss)

* **h\_major** - Major head losses →$ h\\_major=f(\frac{h\_{pump}+htank}{D\\_pipe})\frac{v^{2}}{2g}$
* **h\_minor** - Minor head losses → $h\\_minor=(k\_{entrance}+n\_{elbow}\*k\_{elbow}+k\_{exit})\frac{v^{2}}{2g}$
* **h\_total** - Total head losses → $h\_{total}=h\_{pump}+h\_{tank}+h\_{major}+h\_{minor}$
* **Load** - Load in Joules→ $Load=\frac{Water\_{total}\*rho\*g\*h\\_total}{efficiency}$
* **Load** - Load in MJ → Convert **Load** to MJ

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**Sample Results - Section 2**

Input Values

From Section 1-

Water\_total= 100 m^3

Q= 0.0046 m^3/s

h\_pump=75.1 m

Results

A\_pipe= 0.0082 m^2

v = 0.5637 m/s

f= 0.0203

Re= 57,414

h\_major= 0.2548 m

h\_minor= 0.09443 m

h\_total= 80.4 m

Load = 98.37 MJ

**Section 5** – Size Battery Storage

Instructions: Select a battery model from the list of available manufacturers and/or suppliers. Determine the battery capacity, nominal voltage, and unit cost of the batteries. Create scalars to represent these values. Calculate the energy per battery. Using information from Sections 1 and 2 you will determine the required number of batteries needed.

Battery Manufacturers/Suppliers

1.https://www.aimscorp.net/deep-cycle-batteries/

2. http://www.trojanbattery.com/solar-agm/

3.http://usbattery.com/products/re-renewable-energy-hybrid-systems-backup-power/

Constants given to you in code

DOD = 0.5; % Depth of Discharge (Use 50% for longer life)

 DOD is a measure of how much you let the battery discharge before you start charging it again. Think of your cell phone, do you always wait until it reaches 0% before you plug it in?

RTE= 0.80; % Round trip efficiency - Assume ~80% The amount of energy lost as the battery transfers energy from storage.

Parameters:

* **Capacity -** Charge capacity of the battery in Amp-hours
* **V\_Battery** - Nominal voltage of the battery in Volts
* **UnitCost\_Battery** - Unit cost of the battery
* **StorageDays** - The rule of thumb is to provide for enough storage to last for 3 days. Start with 3 days. You will vary this after the code is functioning.

Calculations:

* **Energy\_Battery** – Energy in the battery in MJ → **V\_Battery\*Capacity\*DOD\*RTE\*(**conversion factor) to change from Watt hr to MJ

Multiple the nominal voltage in Volts by the Capacity in Amp-hours to get the total energy in Wh. Since the battery can only be partially discharged, multiple this number by the depth of discharge (DOD). To account for resistive losses, multiply this number by the round trip efficiency (RTE) .

* **N\_Batteries** - Number of batteries needed → Section 2 calculates the load. From this load calculate the load (in MJ) for the number of days you need to store energy.

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**Sample Results - Section 5**

Input Values

From Section 2-

Load = 98.37 MJ

Capacity = 205 amp-hours

V\_Battery=12 V

StorageDays=3 days

Results

Energy\_Battery = 3.54 MJ

N\_Batteries= 84

**Section 6** – Size Electric Generator

Instructions:

Step 1 - Estimate the Required Generator Power

Convert the Load from MJ to kWh. Multiply the load in kWh by 2 to get the required power of a suitable generator. Assume a runtime of 10 hours. Divide the energy by the time to get the estimated power of the generator.

Step 2 - Select an Appropriate Generator and Perform Calculations

Go the the following site for a list of electric generators:

<https://www.grainger.com/category/portable-and-inverter-generators/electrical-generators/outdoor-equipment/ecatalog/N-1bxu>

Search for a generator with the power you found in Step 1. Click on that generator, then click to open the ***View Product Details*** for that generator. Create a scalar quantity to represent the rated power of the generator, its actual runtime, and. Create a scalar quantity for the fuel tank capacity and the cost of the generator. Calculate the daily fuel consumption.

 Parameters:

* **RunTime\_Estimated** - Estimated daily runtime of the generator (Use 10 hours)
* **P\_Generator\_Actual** - Actual power of the generator that you select
* **Actual\_RunTime** - Actual runtime in hours at 1/2 full power
* **FuelTankCapacity** - Fuel tank capacity of generator
* **InitialCost\_Generator** - Cost of the generator

Calculations:

* **P\_Generator\_Estimated** - Power, in kW, required to meet the load → **Load**(in MJ)/**RunTime\_Estimated\*2**-->convert to kWh
	+ Multiplied by 2 to account for the fact that the generator should be running at half load.
* **P\_Generator\_Effective** - Power, in kW, used by the generator at half load→ **P\_Generator\_Actual/2**
	+ Divide the rated power of the generator by 2.
* **Fuel\_Daily** - Daily fuel consumed by the generator → Calculate daily fuel consumed in gallons by multiplying the **FuelTankCapacity** by the ratio of **Load** (convert to in kWh) to effective power (**P\_Generator\_Effective)** multiplied by the actual runtime(**Actual\_RunTime)**.

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**Sample Results - Section 6**

Input Values

From Section 2-

Load = 98.37 MJ

RunTime\_Estimated= 10 hours

P\_Gen\_Rated= 7.500 kW

RunTime\_Actual = 12 hours

FuelTankCapacity=7.5 gallons

InitialCost\_Generator= 1125

Results

P\_Gen\_Estimated= 5.47 kW

P\_Gen\_Effective= 3.75 kW

Fuel\_Daily = 4.55 gallons**Appendix 1 - References**

Collares-Pereira, M. and Rabl, A. (1979) The Average Distribution of Solar Radiation-Correlations between Diffuse and Hemispherical and between Daily and Hourly Insolation Values. Solar Energy, 22, 155-164.

Duffie, J. A., & Beckman, W. A. (2013). Solar engineering of thermal processes (4th ed.). Hoboken, N.J.: John Wiley & Sons.

Goswami, D & Kreith, Frank & F. Kreider, Jan. (2000). Principles of solar engineering / D. Yogi Goswami, F. Kreith, J.F. Kreider.

Klein, S.A. (1977) Calculation of Monthly Average Insolations on Tilted Surfaces. Solar Energy, 19, 325-329.

Papaevangelou, George & Evangelides, Chris & Tzimopoulos, Christos. (2010). A new explicit equation for the friction coefficient in the Darcy-Weisbach equation, Proceedings of the Tenth Conference on Protection and Restoration of the Environment: PRE10, July 6-9, 2010. Greece Corfu. 166. 1-7.

**Appendix 2 – Variable Used in Instructor’s Code (In order of Usage)**

|  |  |  |  |
| --- | --- | --- | --- |
| **Section Introduced** | **Use in Other Sections**  | **Variable** | **Quantity Represented** |
| 1 | 3, 8 | Latitude | Latitude of site for water pumping system |
|  | 3, 8 | Longitude | Longitude of site for water pumping system |
|  | 4 | Tamb | Monthly average ambient temperature |
|  | 8 | Population | Population town for the water pumping system  |
|  |  | Water\_person | Daily water consumed per person |
|  | 2 | Water\_total | Daily water consumed by the population at the site |
|  | 2 | Q | Water flow rate |
|  |  | h\_water | Distance from ground to top of water table |
|  | 2 | h\_pump | Distance from ground to pump |
| 2 |  | D\_pipe | Pipe diameter |
|  |  | epsilon | Roughness factor for pipe |
|  |  | h\_tank | Height of water storage tank |
|  |  | k\_entrance | Friction factor for pump entrance |
|  |  | k\_elbow | Friction factor for pipe 90 degree pipe elbows |
|  |  | n\_elbow | Number of 90 degree elbows |
|  |  | k\_exit | Friction factor for pipe discharge |
|  |  | v | Mean velocity of pumped water |
|  |  | nu | kinematic viscosity of water at 20 C |
|  |  | Re | Reynold's number |
|  |  | f | Darcy friction factor |
|  |  | g | Gravitational Acceleration |
|  |  | h\_major | Major head loss |
|  |  | h\_minor | Minor head loss |
|  |  | h\_total | Total head |
|  |  | rho | Density of water at 20 C |
|  |  | efficiency | Efficiency of water pumping system |
|  | 4,5,6,8 | Load | Energy needed to pump daily water supply |
| 3 | 8 | MonthNumber | Number of the month (1 - 12) |
|  |  | MeanDay | Mean day of the year for each month |
|  |  | albedo | Ground albedo (reflectivity) |
|  | 8 | Beta | Solar panel tilt angle |
|  |  | H | Monthly ave. diffuse solar radiation - horizontal surf |
|  |  | delta | Solar declination angle |
|  |  | wsh | Sunset angle on a horizontal surface |
|  |  | H | Monthly ave. diffuse solar radiation - horizontal surf |
|  |  | ws | Sunset angle on a tilted surface |
|  |  | Rb | Ratio: Beam radiation on tilted to horizontal surface |
|  |  | Gsc | Global solar constant (average solar irradiance) in kW/m^2 |
|  |  | Gon | Global solar irradiance normal to a surface on a given day  |
|  |  | Ho | Average daily total solar irradiance on a horizontal surface  |
|  |  | KT | Average clearness index |
|  |  | Hd | Average daily diffuse solar radiation  |
|  | 4,8 | Ht | Average daily solar radiation - tilted surface |

|  |  |  |  |
| --- | --- | --- | --- |
| **Section Introduced** | **Use in Other Sections**  | **Variable** | **Quantity Represented** |
| 4 | 8 | Pmax | Rated maximum power of solar panel at STC |
|  | 8 | alpha | Temperature factor for power loss of solar panels |
|  | 8 | Eta | Rated efficiency of solar panels |
|  | 8 | Apanel | Area of solar panels |
|  | 7 | UnitCost\_Panel | Cost of one solar panel |
|  | 7,8 | N\_Panels | Number of solar panels |
| 5 |  | DOD | Depth of discharge of the battery |
|  |  | RTE | Round trip efficiency of the batteries |
|  | 8 | Capacity | Fully charged capacity of battery in Amp-hours |
|  | 8 | V\_Battery | Nominal voltage of one battery |
|  | 7 | UnitCost\_Battery | Cost of one battery |
|  |  | Energy\_Battery | Usable energy available in one battery |
|  | 8 | Storage\_Days | Number of days load can be powered by batteries alone |
|  | 7,8 | N\_Batteries | Number of batteries |
| 6 |  | RunTime\_Estimated | Estimated running time of the generator |
|  |  | P\_Gen\_Estimated | Estimated power of the generator |
|  | 8 | P\_Gen\_Rated | Rated power of the generator |
|  |  | P\_Gen\_Effective | Effective power of the generator (½ rated power) |
|  |  | RunTime\_Actual | Actual runtime of generator |
|  |  | FuelTankCapacity | Volume capacity of the fuel tank in gallons |
|  | 7,8 | InitialCost\_Generator | Initial cost of the generator |
|  | 7 | Fuel\_Daily | Daily amount of fuel used to meet the load |
| 7 |  | InitialCost\_Solar | Initial costs of the solar energy system  |
|  |  | UnitCost\_Fuel | Unit cost of fuel for the generator |
|  |  | DailyCost\_Fuel | Daily fuel cost to meet the load using the generator |
|  | 8 | YearlyCost\_Fuel | Yearly fuel cost to meet the load using the generator |
|  |  | d | Discount rate of money |
|  |  | n | Year of system operation (Use in Matlab Summation) |
|  | 8 | N | Number of years for Accumulated generator cost to meet solar energy system costs |
|  | 8 | Year | Years of system was operation |
|  | 8 | YearlyCost\_Solar | Yearly cost to operate the solar energy system |
|  | 8 | AccumulatedCost\_Solar | Accumulated costs of the solar energy system |
|  | 8 | YearlyCost\_Generator | Yearly costs of the electric generator system |
|  | 8 | AccumulatedCost\_Generator | Accumulated costs to operate electric generator system |
| 8 |  | T | Table of values of yearly and accumulated costs |
|  |  | Energy\_Solar | Average energy generator by the solar energy system each month |

**Appendix 2 - Sample Output**

System Sizing



Energy Per Month from PV System



Economic Comparison Table

