

# Solar Decathlon Load Profiling

## Project Report

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## Executive Summary

The U.S. Department of Energy Solar Decathlon is an international competition that tests 20 selected colleges to design, build, operate the most attractive, effective and energy-efficient solar-powered home. The University of California Davis was selected as one of the participants for the 2015 competition. The UC Davis team has decided to delegate areas of architecture, design, engineering, and sociology to specific courses and extracurriculars to fully engage students and maximize productivity. The course, Path to Net Zero Energy: A hands on approach, was one course that was asked to contribute to the Solar Decathlon competition. In this course, a team of both graduate design students and engineers were selected in order to create and showcase an energy load profile to estimate the electrical energy requirements needed throughout the competition, and to research and brainstorm innovative energy saving ideas. The energy load profile team worked with Tom Ryan, the Solar Decathlon Design & Engineering Coordinator, in order to successfully obtain an accurate energy load profile model that could immediately assist the Solar Decathlon members and estimate the size of the solar panel needed to provide energy for the home..

The energy load profile was created as an adjustable computer model by using Microsoft Excel. The competition committee gives an extensive list of rules for the competition and states exactly what appliances, lighting, hot water, space conditioning conditions, electric car and electronics are needed to be included in the solar-powered home. Additionally, scheduling for all of the appliances throughout the competition is given on a every half-hour basis. Therefore, to obtain an assessment of the electrical energy requirement by the home, the specific appliances with known wattages, a specific electrical car with charging time, a space conditioning system, a hot water system, and lighting of the home all needed to be carefully selected. After determining the power of each the various appliances and systems in the house, the wattages could be multiplied by the time in which they were operating to find the energy in kWh consumed. Various appliances and electric car models were compared to examine which were the most energy and cost efficient. Additionally, various space conditioning and hot water systems were compared and selected based on energy efficiency and ease of implementation. In order to determine the electrical energy for the space conditioning, in addition to selecting a space conditioning system, the total heat load to be provide or removed needed to be determined. This was done by using a simplified heat model obtained from UC Davis Professor Mark Modera. We were able to successfully create an energy load profile spreadsheet that estimated the energy consumed every half hour for the entire operational part of the competition. Summing the energy consumption of the competition, we estimate total energy usage to be about 197 kWh, requiring at least 3.65 kW in solar panels to be zero net energy.

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## Project background

The Solar Decathlon is an international competition by the U.S. Department of Energy that tests 20 collegiate teams to design, construct and operate the most attractive, effective and energy-efficient solar-powered home. The contest consists of ten sub-contests including contests in architecture, market appeal, engineering, communications, affordability, comfort zone, hot water, appliances, home entertainment and energy balance. UC Davis was selected as one of the twenty schools to compete in the 2015 Solar Decathlon in Irvine California. The UC Davis team has decided to delegate areas of architecture, design, engineering, and sociology to specific courses and extracurriculars to fully engage students. One of the courses selected to assist the Davis Solar Decathlon team was Path to Net Zero Energy: A hands on approach.

Four students in the Path to Net Zero Energy were selected to be part of a load profiling team to aid the Solar Decathlon team in determining how much energy would be needed by the house throughout the competition. The objective of the load profiling team was to create an hourly load profile of the ten operating days of the Solar Decathlon home that considered energy efficient appliances, an electric car, hot water, cooking, lighting, heating and cooling, and followed the set competition schedule. The load profile could then be used to determine the total amount of electrical energy needed by the home, the peak amount of electricity consumed by the home, and the sizing requirements for solar panels to be placed on the house. Tom Ryan, the project's Design & Engineering Coordinator, was the client of the project and provided the team with the necessary objectives needed to complete the project successfully and fully provide beneficial information to the UC Davis Solar Decathlon Team.

## Prior Art

In looking for data on typical household electrical energy consumption, we found a study done by KEMA Inc. prepared for the California Energy Commission.<sup>1</sup> It reports the energy used by different appliances in over 20,000 California homes in 2009. The data is a combination of surveys sent out to these households and electric billing data from utilities providers (Pacific Gas and Electric Company, Southern California Edison Company, San Diego Gas & Electric

Company, Southern California Gas Company, and Los Angeles Department of Water and Power). Summarizing the data, we created the chart shown in Figure 1, breaking down the energy consumption by end use. The largest end uses were space heating, water heating, and appliances and the total electrical energy usage was 7600 kWh. Over a nine-day period (the time that the solar decathlon house will be in operation), this equates to about 190 kWh. Given that the house will be designed with the most energy efficient measures, we expected to arrive at a total energy usage much less than this. Also, the data that this is calculation is based on accounts for all of the electricity used in homes, including those that use natural gas. Thus, the total energy usage for an electric-only house should be greater.

## Average Annual Energy Consumption

Total Consumption : 7,600 kWh

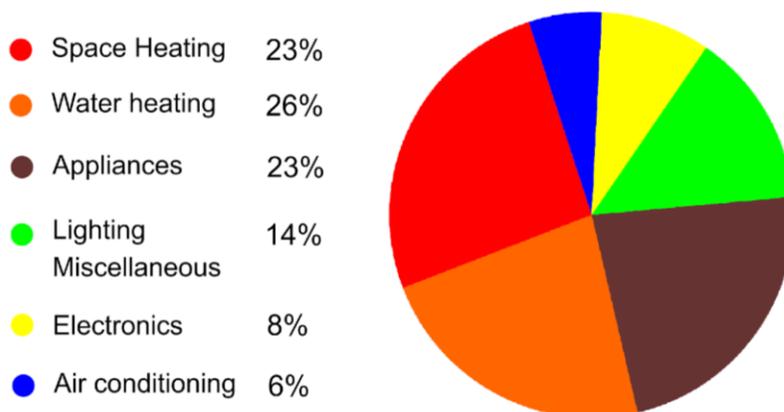


Figure 1. Pie chart showing the relative energy usage in California homes. Data comes from the 2009 California Residential Appliance Saturation Study.<sup>1</sup>

## Methodology

The first step in building the load profile began with the competition rules.<sup>1</sup> Inside, it lays out all of the different loads and appliances required for the house, such as running the refrigerator, maintaining a constant temperature, and charging an electric car. The rules also specify exactly when each one must be operated and tested. Using the competition schedule (see Appendix A) we developed our own spreadsheet for tallying energy usage by each appliance on a half-hourly basis.

Energy Star was the main source of information for determining energy usage. Information on all of the current certified models of dishwasher, clothes washer, clothes dryer, refrigerator, water heater, and air conditioning unit were taken from Energy Star listings and compared for both energy efficiency and meeting competition standards. For some equipment, (dishwasher, clothes washer, and clothes dryer) listed models had little variation and so the metrics (typically the rated annual energy usage) for the highest efficiency model were used. Where applicable, the energy usage per/cycle was directly incorporated into the spreadsheet per specified operation. When only the annual energy usage was given (such as with the water

heater), the energy consumption was divided evenly into half-hourly segments and assumed constant throughout the competition. Loads for which more specific consideration was given or more detailed analysis was done are presented below.

### *Water Heater*

The competition has periodic hot water draws of 15 gallons, and so the water heater was given the additional consideration of the listed First Hour Rating, being the number of gallons of hot water that can be supplied in the first hour of operation, starting with a full tank. All of the water heaters exceeded this value by more than double, so we assume that there will be no issues with the capacity meeting the peak demand.

Heat pump water heaters are the only type of water heaters certified by Energy Star that run solely on electricity. We recommend the Stiebel Eltron Accelera 300 model based on its high efficiency and thus relatively low energy usage (1391 kWh/year). This value is based on an assumed daily draw of 64 gallons of hot water<sup>3</sup>, more than double what is expected for any given day of the competition. Thus, the rated energy usage was cut in half and averaged over a 9 day period.

### *Refrigerator*

Four models of refrigerator were compared, ranging from 171 to 398 kWh/year in annual energy use (see Appendix B).<sup>4</sup> The most efficient model (Sun Frost RF-12) also had the smallest capacity (10.1 cu.ft.), but still met competition criteria. While using the least amount of energy, it is also the most expensive (\$2400) and, albeit subjectively, least attractive. The GE GTH17BBC is rated at 300 kWh, has a total capacity of 16.5 cu.ft. and looks like a standard refrigerator with top freezer and no other features. The retail price for this model was unable to be determined. Next up in energy usage is the Whirlpool WRT371SZB, at 364 kWh. This model is similar to the GE model, but slightly larger in capacity (21.1 cu.ft.). The retail price found was also the cheapest, at \$800. Lastly, the Samsung RF261BIAESR is the most energy intensive, using 398 kWh of energy/year. This is due in part to its larger capacity (25.5 cu.ft.). However, it is likely the most appealing, having a french door style opening, internal water dispenser, and ice maker. Its retail price is \$2200. Out of the four models discussed, we suggest the Whirlpool for its balance of energy use, appeal, and cost.

### *Electric Car*

Competition rules state that the electric vehicle used must be listed on the DOE Energy Efficiency & Renewable Energy all-electric vehicles website. Thus, a comparison was made between all 11 models of cars listed.<sup>5</sup> The metrics used to evaluate the cars were the efficiency (in units of kWh/100 miles) and the charging time. Charging time was considered to ensure that the car would be operable during days in the competition when there are two driving tasks. 4 of the 11 cars have comparably high efficiencies, between 28-29 kWh/100 miles. Of these 4 cars, the model with the quickest charging time is the 2014 Fiat 500e, which is the model we recommend.

### *Lighting*

The competition rules state that to receive full points all interior and exterior house lights must be kept on during the specified periods of time, and lighting must be considered adequate by a visual inspection. The amount of electricity used for lighting was estimated by first determining the light sources that would be in the home, then finding the electricity consumed by observing the wattage of the appliances and the hours of operation for them. A simple estimate of the number of light sources for each type of room e.g. kitchen or bedroom was found from research data of a typical energy efficient American home from the California Lighting Technology Center (CLTC) in Davis. The wattages of the light sources was also determined from CLTC data for typical wattage values of various energy efficient light sources used for lighting different locations in a home e.g. bedroom, kitchen or exterior. The times that the lights were to be on was given in the schedule provided in the competition rules and therefore the kWh of electricity used by the lighting could be found by multiplying the wattage of the light source by the time the light was on.

### *Heating*

The competition rules state that the house is to be maintained between the temperature range of 71-76 degrees F. A heat transfer model created by UC Davis Professor Mark Modera was used to estimate the heat loss and heat gain by the house, and thus the electrical load needed to maintain the house at the specified temperature range. The Modera model estimates the hourly heat transfer into and out of a simplified box shaped house, using various house specifications as input parameters (i.e. dimensions, number of windows, R-value of insulation, and climate and location data, including exact longitude and latitude, outside temperature, and wind velocity). From these inputs the model can calculate the total heat transfer by summing the radiation, convection and conduction that is occurring in the house. The final outputs from the model are an hourly and total daily amount of BTU's either gained or loss by the house.

For the building input parameters, one of the possible Solar Decathlon designs proposed by Mahan Soltanzadeh was considered. The square footage of the house was expected to be 1000 square feet, and therefore the dimensions for the box model was chosen to be 31.62 ft. by 31.62 ft. (square-root of 1000). Four 2 ft. by 2 ft. windows on the west and east side of the house were inputted into the model to be consistent with the design proposal. Additionally, an R-value of 40 was chosen for the walls and roof of the home since this was the goal R-value stated in the Solar Decathlon Davis Team's proposal. An R-value of 40 could be obtained by using compressed straw insulation, which can possess a R-value of up to 55.

The climate data was inputted from a typical meteorological year (TMY) file that contained weather data for Long Beach California as there was not TMY data specifically for Irvine; Long Beach is within 25 minutes of Irvine and typically has similar weather to Irvine. The data for October 1st was used since this is around the time that the competition is held. It is important to note that Irvine's weather generally does not deviate that much seasonally nor daily and therefore accurate weather predictions can be obtained. The model considered the outside dry bulb temperature, the wind speed, the normal sunlight radiation onto the roof of the home, and the horizontal sunlight radiation onto the walls of the home.

The internal gains were found by taking the sum of all of the electrical appliances that were operating in a specific hour during day 11 of the competition from the power load spreadsheet and converting this number from kilowatts to watts. The lighting was inputted in the

same manner by observing when the competition schedule required the lighting to be on. It was estimated that zero people would be in the house during non-operating hours, four people during house operating times and on average eight people would be in the house during public viewing hours.

The electrical load required to heat/cool the house was determined by taking the hourly heat gain from the Modera model, and multiplying by an assumed HSPF (heating seasonal performance factor) rating of 12 BTU/Wh.

## Results & Discussion

Based on the methodology discussed in the previous section, we developed a complete load profile for the competition, shown in Figure 2. For any given day, there are between 1 and 3 noticeable peaks that occur. This corresponds to times in the competition when multiple loads must be tested simultaneously; typically, the dishwasher, clothes washer, clothes dryer, and cooking unit operations all occur at once. Adding up all of the loads over the 9 days of the competition, we determined that the house would use about 197 kWh of energy in total (see Appendix C). A simple calculation shows that this requires 3.65 kW in photovoltaic power (assuming an average of 6 full sun hours of charging time) in order to operate the house at zero net energy.

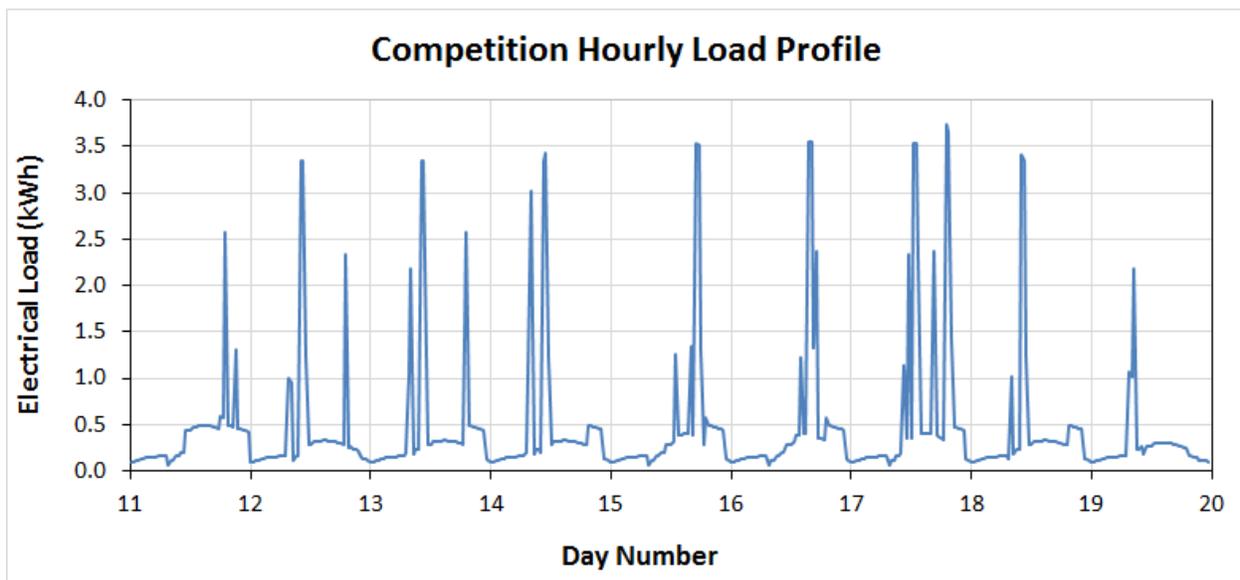


Figure 2. Predicted load profile over the course of the competition.

Comparing the total energy usage to the initial prediction based on prior art, the values are practically identical. While we initially believed that the house would use significantly less energy than 190 kWh, we forgot to account for charging of the electric vehicle. This makes up nearly 30% of the energy usage, as shown in Figure 3. Most California homes do not charge their own cars, and would require significantly more energy to do so, thus we believe our estimations to be reasonable for an efficiently designed electric-only home. Based on the scoring function of the competition, maximum points are awarded for a measured consumption

of 175 kWh or less, and reduces linearly down to 0 points for an energy consumption of 300 kWh or more. Thus, with our predicted energy usage of 197 kWh, 82% of the points for the Energy Consumption Subcontest would be earned.

Figure 3 shows the relative energy usage in the house between the different loads. The two largest contributors are the electric car and the space conditioning, each one making up about 30% of the total energy usage. This is followed by the lighting, water heater, and cooking unit, which altogether make up another 26%. The energy used by the electric car is straightforward and dictated by the driving requirement of the competition. Thus, the greatest potential for energy savings and maximized points is in the space conditioning. However it also provides the greatest source of uncertainty.

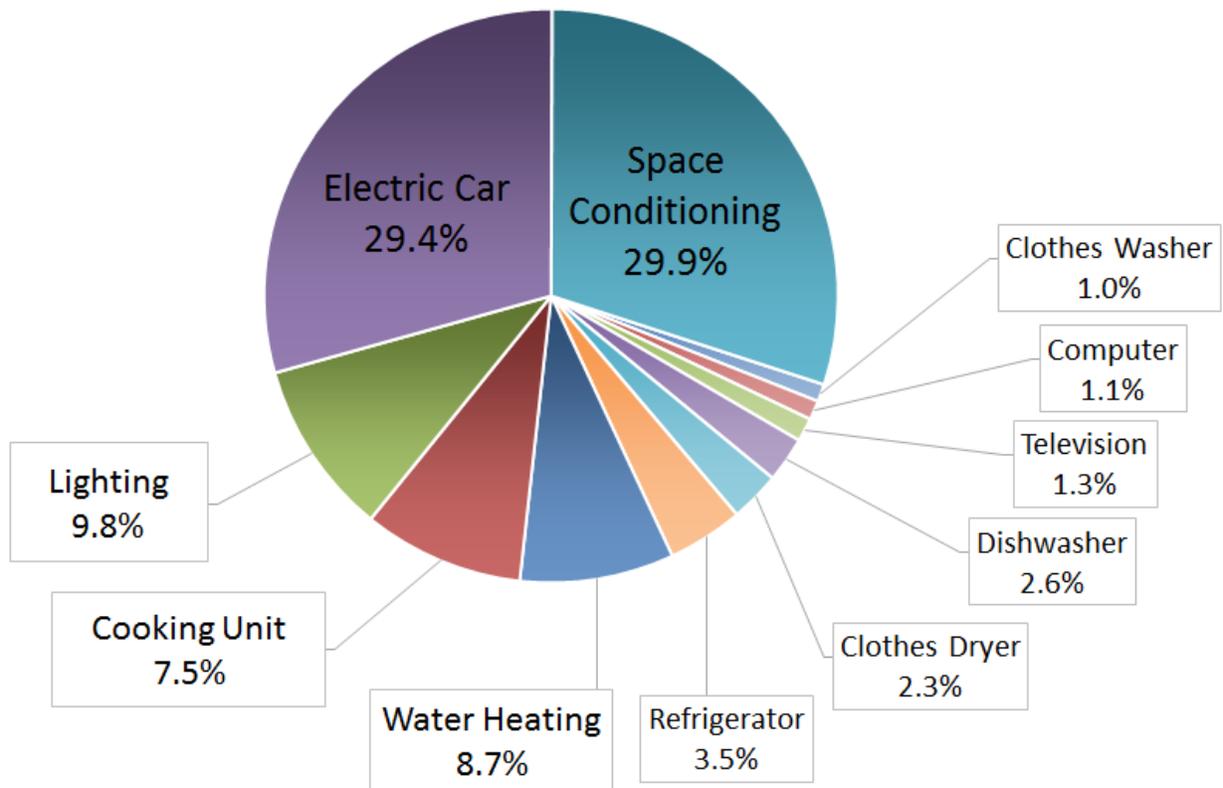


Figure 3. Relative energy use of the individual loads.

It is important to note how changes in the parameters can affect the daily BTU needed to heat or cool the home since many of the parameters are not determined yet. By changing the R-value of the walls of roof of the house by a factor of 10 there is about a 2,000 BTU or 166.7 Wh daily increase. This means about a 1.5 kW total increase for the competition can be conserved from the house by using an insulation with an R-value of 40 rather than 30. By not including any windows on the house also resulted in about a 2,000 BTU or 166.7 Wh difference. This demonstrates the importance that adding windows can have towards the energy input needed for heating and cooling the home. The window surface area should be minimized and/or the overall heat transfer coefficient of the windows should be increased while maximizing the

window locations for lighting and acetic value in order to obtain minimal energy requirements while still providing the design benefits of windows.

The temperature that the house is kept at is perhaps the most important factor for how many daily BTU's are needed for heating and cooling. Decreasing the temperature by 5 degrees C resulted in 14,000 more BTU's or about 1,150 Wh needed for daily heating and cooling, which can translate to an additional 12 kWh needed during the competition. This demonstrates the importance of using a good temperature control system and maintaining the house at the upper temperature limit during the day in order to minimize the energy needed for space conditioning. Additionally, solar radiation was found to be a major contributor to the heat gain of the building as expected. Finding methods to reduce the radiant absorptivity of the home could also significantly decrease the energy needed to cool the home.

## Conclusions & Recommendations

By compiling information on energy usage of various household loads, a reasonable estimate of the load profile for the competition was established. This led to a total energy usage of 197 kWh. In order to generate this much electricity over 9 days, 3.65 kW in PV are required. There are several ways to improve upon this initial estimate, the greatest of which is in reassessing the heat transfer through the house needed to maintain the competition specified temperature.

Although the current heat model estimation gives a good baseline value for the amount of energy needed to space condition the home, many improvements can be made in the future. Currently, the design of the home is not finalized and having more accurate information on the dimensions of the house, the actual R-value of the roof and wall materials, and the total surface area of the windows and walls will provide a more accurate estimation of the energy usage. The weather data from the TMY for October used was from over thirty years ago and therefore more current weather data for October in Irvine may be available and give a more accurate prediction of the weather conditions for the competition. As the final appliances and light sources are determined, their power ratings can be inputted into the model as well. Also, the number of people in the home at a given time can be changed accordingly to a more accurate representation of the people expected to be present. Currently, the heat model is only for one day. A heat model used for each day that accounts for the unique daily competition scheduling would provide a more accurate estimation of the space conditioning of the home. The space conditioning of the home currently is estimated to be the largest source of energy use and therefore strategies to reduce the heating and cooling of the home would be most beneficial in reducing the total energy used throughout the competition.

In the future the energy profile spreadsheet could be easily adapted to model housing for migrant workers. It would be assumed that the migrant workers would live in a house of a similar design with the same appliances, however changes in appliances e.g. TV could be adjusted in the model or building information e.g. square footage could also be quickly changed. A major adjustment that must be made to the model would be the scheduling of the appliances. This could be done after researching the typical behavior of a migrant worker and then approximating when certain electrical loads are needed for various tasks. The climate data would also need to be changed in the heat model for the location of the migrant worker housing to adjust for the

heating and cooling energy requirements. Most likely, only an average work day and average off day would be needed to accurately predict a larger time scale for a migrant worker (all work day electrical consumptions would be assumed to be the same and also all non-work days electrical consumptions would be assumed to be the same).

## References

- [1] KEMA Inc. 2010. *2009 California Residential Appliance Saturation Study*. California Energy Commission. CEC-200-2010-004.
- [2] U.S. Department of Energy Solar Decathlon 2015 Official Rules. <[http://www.solardecathlon.gov/past/2015/pdfs/2015\\_rules.pdf](http://www.solardecathlon.gov/past/2015/pdfs/2015_rules.pdf)>
- [3] 10 CFR Part 430, Subpart B, Appendix E to Subpart B of Part 430 - Uniform Test Method for Measuring the Energy Consumption of Water Heaters. (n.d.). *LII / Legal Information Institute*. Retrieved May 10, 2014, from <http://www.law.cornell.edu/cfr/text/10/part-430/subpart-B/appendix-E>
- [4] ENERGY STAR Certified Residential Refrigerators | ENERGY STAR Certified Products | US Environmental Protection Agency. (2013, August 23). *data.energystar.gov*. Retrieved May 3, 2014, from <https://data.energystar.gov/Government/ENERGY-STAR-Certified-Residential-Refrigerators/dgpf-upjt?>
- [5] All-Electric Vehicles: Compare Side-by-Side. (n.d.). *All-Electric Vehicles: Compare Side-by-Side*. Retrieved May 7, 2014, from <http://www.fueleconomy.gov/feg/evsbs.shtml>

# Appendix

## Appendix A: Sample Competition Schedule

Sun (Day 14)									
Rules Section	Contest Type	Total Pts Available	Total # of tasks or periods	Daily # of tasks or periods	Daily Points Available				
Temperature	MEAS	75,000	574	60	2,613				
Humidity	MEAS	25,000	574	60	1,253				
Refrigerator	MEAS	10,000	766	96	1,253				
Freezer	MEAS	10,000	766	96	1,253				
Clothes Washer	TASK	18,000	8	1	2,000				
Clothes Dryer	TASK	32,000	8	1	4,000				
Home Electronics	TASK	10,000	34	3	0,882				
Dishwasher	TASK	17,000	5	1	3,400				
Cooking	TASK	15,000	6	1	2,500				
Commuting	TASK	100,000	8	1	12,500				
Hot Water	TASK	50,000	16	1	3,125				
Lighting	TASK	25,000	52	6	2,895				
DAILY AVAILABLE POINTS					44,291				
CUMULATIVE AVAILABLE POINTS					148,957				
Team/organizer meeting									

Mon (Day 15)									
Rules Section	Contest Type	Total Pts Available	Total # of tasks or periods	Daily # of tasks or periods	Daily Points Available				
Temperature	MEAS	75,000	574	96	12,544				
Humidity	MEAS	25,000	574	96	4,181				
Refrigerator	MEAS	10,000	766	96	1,253				
Freezer	MEAS	10,000	766	96	1,253				
Jury Walkthroughs C1,2,3,4	JURIED	-	-	-	-				
Clothes Washer	TASK	18,000	8	2	4,000				
Clothes Dryer	TASK	32,000	8	2	8,000				
Home Electronics	TASK	10,000	34	5	1,471				
Hot Water	TASK	50,000	16	3	9,375				
Commuting	TASK	100,000	8	1	12,500				
Lighting	TASK	25,000	52	8	3,946				
DAILY AVAILABLE POINTS					58,423				
CUMULATIVE AVAILABLE POINTS					207,380				
Team/organizer meeting									

Tues (Day 16)									
Rules Section	Contest Type	Total Pts Available	Total # of tasks or periods	Daily # of tasks or periods	Daily Points Available				
Temperature	MEAS	75,000	574	96	12,544				
Humidity	MEAS	25,000	574	96	4,181				
Refrigerator	MEAS	10,000	766	96	1,253				
Freezer	MEAS	10,000	766	96	1,253				
Jury Walkthroughs C1,2,3,4	JURIED	-	-	-	-				
Home Electronics	TASK	10,000	34	6	1,766				
Commuting	TASK	17,000	5	1	3,400				
Dishwasher	TASK	17,000	5	1	3,400				
Hot Water	TASK	50,000	16	3	9,375				
Commuting	TASK	100,000	8	1	12,500				
Lighting	TASK	25,000	52	8	3,946				
DAILY AVAILABLE POINTS					62,617				
CUMULATIVE AVAILABLE POINTS					269,997				
Team/organizer meeting									

Inbound period
  Task Period
  Event/activity
  Public exhibit hours
  Juried contest results
  Tasks requiring observer
  Food preparation and cooking
  Jury walkthroughs

Appendix B: Refrigerator Comparison

Model	Sun Frost RF-12	GE GTH17BBC****	Whirlpool WRT371SZB*0*	Samsung RF261BIAESR
Annual Energy Use (kWh)	171	300	364	398
Type	Top Freezer	Top Freezer	Top Freezer	French Door
Fridge Capacity (ft <sup>3</sup> )	8.07		14.95	17.6
Freezer Capacity (ft <sup>3</sup> )	2.05		6.13	7.9
Total Capacity (ft <sup>3</sup> )	10.1	16.5	21.1	25.5
Cost	\$2,400	?	\$800	\$2,200
Comments	Lowest energy; no features; less attractive	Low energy; larger capacity; seemingly unavailable; brand name	Large capacity; brand name; cheaper; medium energy usage	Brand name; style; large capacity; higher energy use; more expensive; internal water dispenser and ice maker

Appendix C: Competition Cumulative Energy Use

