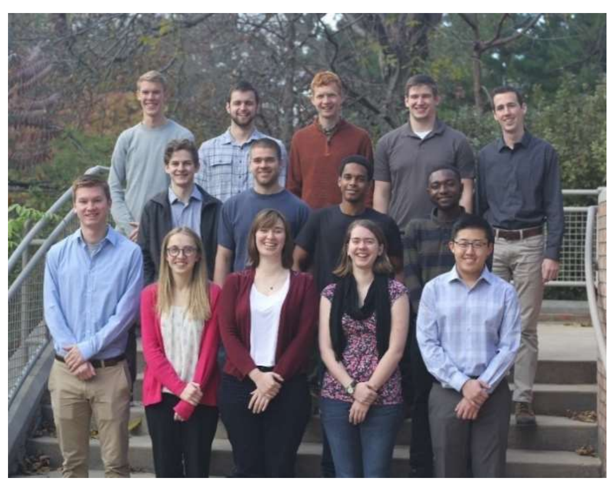
Energy Rebound Project

Dr. Heun and Dr. Brockway

Engineering 333: Thermal Systems Design

December 18, 2019

ENGR 333: Section A
Teams 1 – 6



ENGR 333: Section B
Teams A – D

Introduction

Today, many institutions and individuals see energy efficiency as an important issue; reducing energy consumption is thought to decrease demand for fossil fuels and consumes energy more sustainably. However, while more efficient devices can save users both energy and money, they do not always result in less energy use as a society. This discrepancy between expected and actual energy savings is called the rebound effect. This can be a result of several factors: increased use of the device drawing more energy, manufacturers using more energy to create the new device, or money saved by the users being re-spent in the economy. The combination of these three factors produces an economy-wide rebound where the market saves less energy than expected.

Method

The Engineering 333 class at Calvin University has been conducting research with the goal of determining the economy-wide rebound effect of adopting new energy efficient technologies. Each class broke into teams, with each team investigating the rebound effect of two different devices. There were two requirements each team had to meet with their device selection. First, when selecting the two devices, one had to be "small" (~less than $500 initial cost), and one had to be "large" (at least $1000 initial cost). The second requirement was that at least one energy efficiency intervention had to be relevant to life on Calvin's campus.

The data produced from this study was found in a variety of ways. Each team involved in the project found studies pertaining to their devices that contained data such as direct energy consumption, device-level rebound, and lifetime costs. When studies did not provide pertinent numbers, equations and other estimating tools were used to find these values. Analysis for rebound was found by determining device-level rebound and then connecting that to economy-wide rebound. This was done using Equation 1 below.

$$Re_{EW} = Re_{dev} + \varepsilon + (1 - Re_{dev} - \gamma)kIp_e \qquad \text{(Equation 1)}$$

where k is a constant based on the marginal propensity to consume, I is the energy intensity of the economy which relates GDP to energy, p_e is the price of energy for the given device, and γ is the cost to implement. Note that this equation is directly dependent on the three main contributing factors:

- Device-level rebound (Re_{dev})
- Embodied energy rebound (ε)
- Re-spending rebound ($(1 - Re_{dev} - \gamma)kIp_e$)

The contributions of each of these terms could then be used to determine the driving factor for energy backfire from each device – direct device-level rebound, embodied energy in manufacturing, or spending of freed cash in the economy.

Results

After some analysis it was determined that the re-spending effect had the greatest contribution toward the overall economy-wide rebound for most of the energy efficiency interventions, as can be seen in Figures 1 and 2. According to data seen in these figures, an overall trend is that several of the devices studied go over 100% economy-wide rebound, and therefore will backfire. It should also be noted that the re-spending effect has the largest impact on the overall economy-wide rebound. These results and their high dependence on the re-spending effect also suggests a high dependence on the Marginal Propensity to Consume (MPC), which is used to calculate re-spending. For a sensitivity study on the how these results depend on the MPC see Appendix A2.

Conclusion

Economy-wide rebound is most significantly impacted by re-spending rebound. Though devices vary, the energy intensity of the economy means that the economic gain of an energy efficiency device equates to increased energy use as cost savings ripple through an economy dependent on energy to function.

Because of this energy intensity, there is tension between energy efficiency and energy usage: energy efficiency can potentially be damaging in the case of economy-wide backfire. Because governments strive for a constantly growing economy, they will naturally have an economy that requires more energy.

Energy efficiency lies at the very heart of this growth cycle; as more energy efficient devices are created, they naturally create cost savings. These savings can be reinvested into the economy through re-spending which in turn causes more energy usage. This development is not necessarily a bad thing, however, when the economy is based on a non-renewable energy infrastructure, a problem starts to arise. With today's fossil-fuel-based energy infrastructure, as the economy grows, it uses more energy and in turn emits more carbon dioxide which increases global warming.

The economic development due to energy efficient savings is exactly what a healthy economy should have, the problem is the energy system that the economy relies on. With a non-renewable energy infrastructure, it is possible for energy efficiency developments to hurt the environment due to the impending economic growth it causes and the associated re-spending effect. However, it would be possible for this tension to disappear if a renewable infrastructure could be developed.

Another possible solution to mitigate some of the negative environmental effects of rebound is a green revolving fund. These funds take money that is saved through energy efficiency and recycle it back into more energy efficient projects. This way, the additional money is actively being put towards environmentally friendly projects which decreases negative side of the additional energy implications.

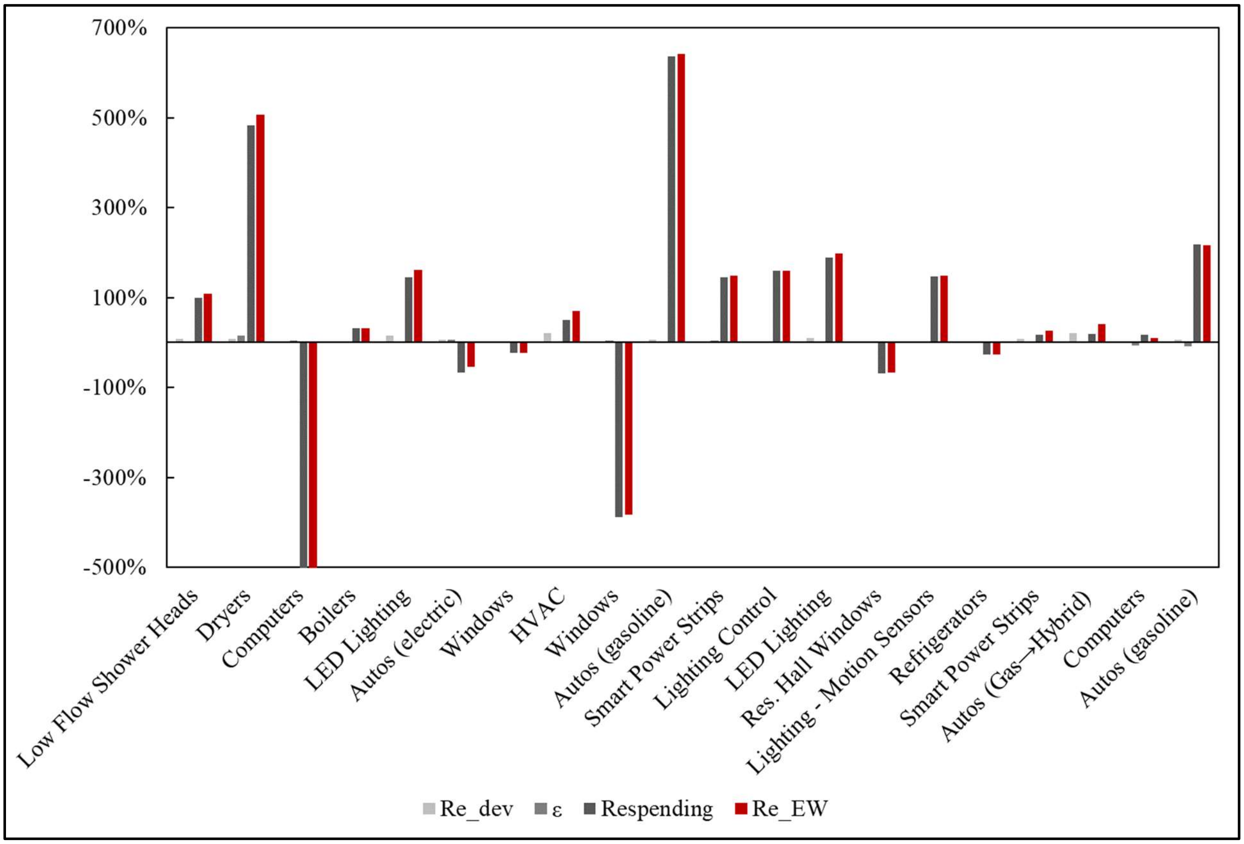


Figure 1: Bar graph comparing the percentages of total energy rebound across all devices

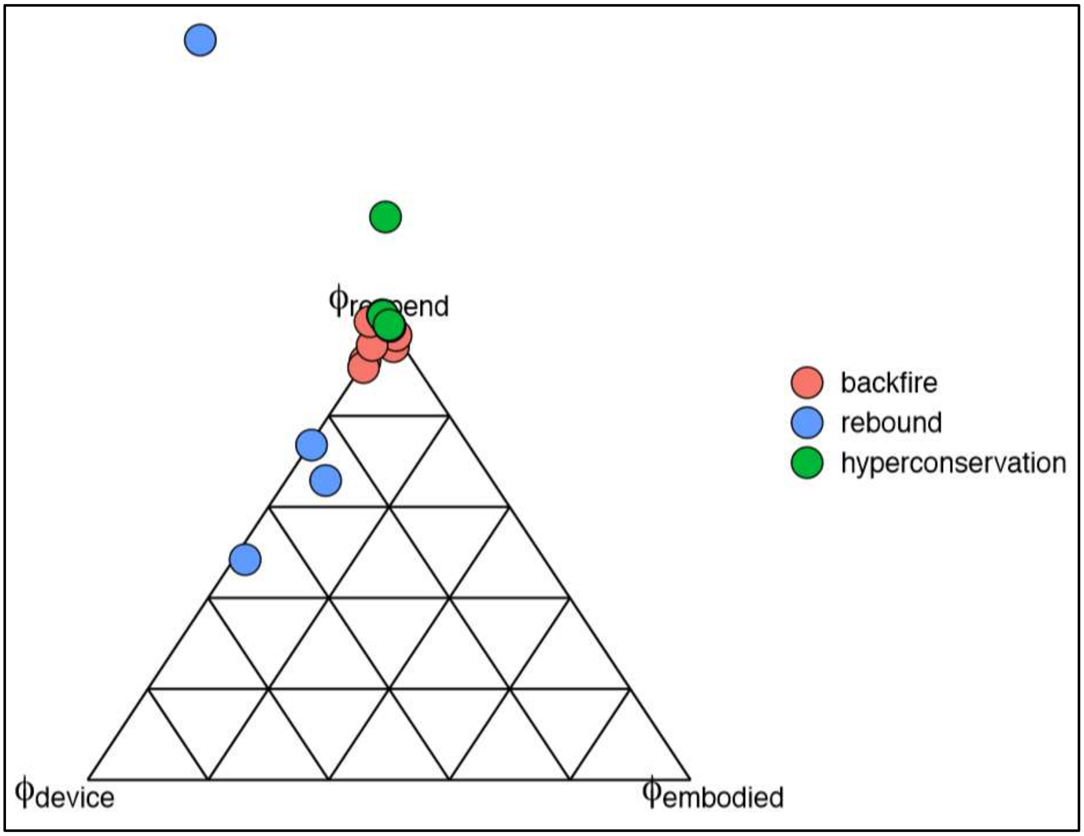


Figure 2: Ternary graph comparing the percentages of energy rebound effect.

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Appendix A: Executive Summary

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Executive Appendix A1: Equations

The three pieces of embodied energy are calculated using Equations A1.1 through A1.3

$$Re_{dev} = 1 - \frac{\dot{E}_{sav,dev,dir,actual}}{\dot{E}_{sav,dev,dir,expected}} \quad \text{(Equation A1.1)}$$

$$\varepsilon = \frac{\dot{E}_{cost,dev,emb}}{\dot{E}_{sav,dev,dir,expected}} \quad \text{(Equation A1.2)}$$

$$\gamma = \frac{\dot{C}_{impl}}{p_E \dot{E}_{sav,dev,dir,expected}} \quad \text{(Equation A1.3)}$$

Where the energy values mentioned above are calculated using Equations A1.4 through A1.9.

$$\dot{E}_{cost,dev,emb} = \dot{E}_{emb,EE} - \dot{E}_{emb,base} \quad \text{(Equation A1.4)}$$

$$\dot{E}_{sav,dev,dir,expected} = \dot{E}_{dir,base} - \dot{E}_{dir,EE} \quad \text{(Equation A1.5)}$$

$$\dot{E}_{sav,dev,expected} = \dot{E}_{sav,dev,dir,expected} - \dot{E}_{cost,dev,emb} \quad \text{(Equation A1.6)}$$

$$\dot{E}_{sav,dev,dir,expected} = 1 - \frac{\dot{E}_{sav,dev,dir}}{1 - Re_{dev}} \quad \text{(Equation A1.7)}$$

$$\dot{E}_{sav,dev,dir} = (1 - Re_{dev})\dot{E}_{sav,dev,dir,expected} \quad \text{(Equation A1.8)}$$

$$\dot{E}_{sav,dev} = \dot{E}_{sav,dev,dir} - \dot{E}_{cost,dev,emb} \quad \text{(Equation A1.9)}$$

The cost values mentioned above are calculated using Equation A1.10.

$$\dot{C}_{impl} = \dot{C}_{repl,EE} - \dot{C}_{repl,base} \quad \text{(Equation A1.10)}$$

Executive Appendix A2: Graphs and Values

Energy Price Constants	
Natural Gas - Commercial [$/MJ]	$ 0.0105
Natural Gas - **Calvin** [$/MJ]	$ 0.0044
Gasoline [$/MJ]	$ 0.0211
Electricity - Commercial [$/MJ]	$ 0.040
Electricity - **Calvin** [$/MJ]	$ 0.0227
Economic Parameters	
Marginal Propensity to Consume (MPC) [-]	0.95
k [-]	19
Energy Intensity of the Economy (I) [MJ/$]	3.89

Figure A2. 1: Constants used across groups for calculations

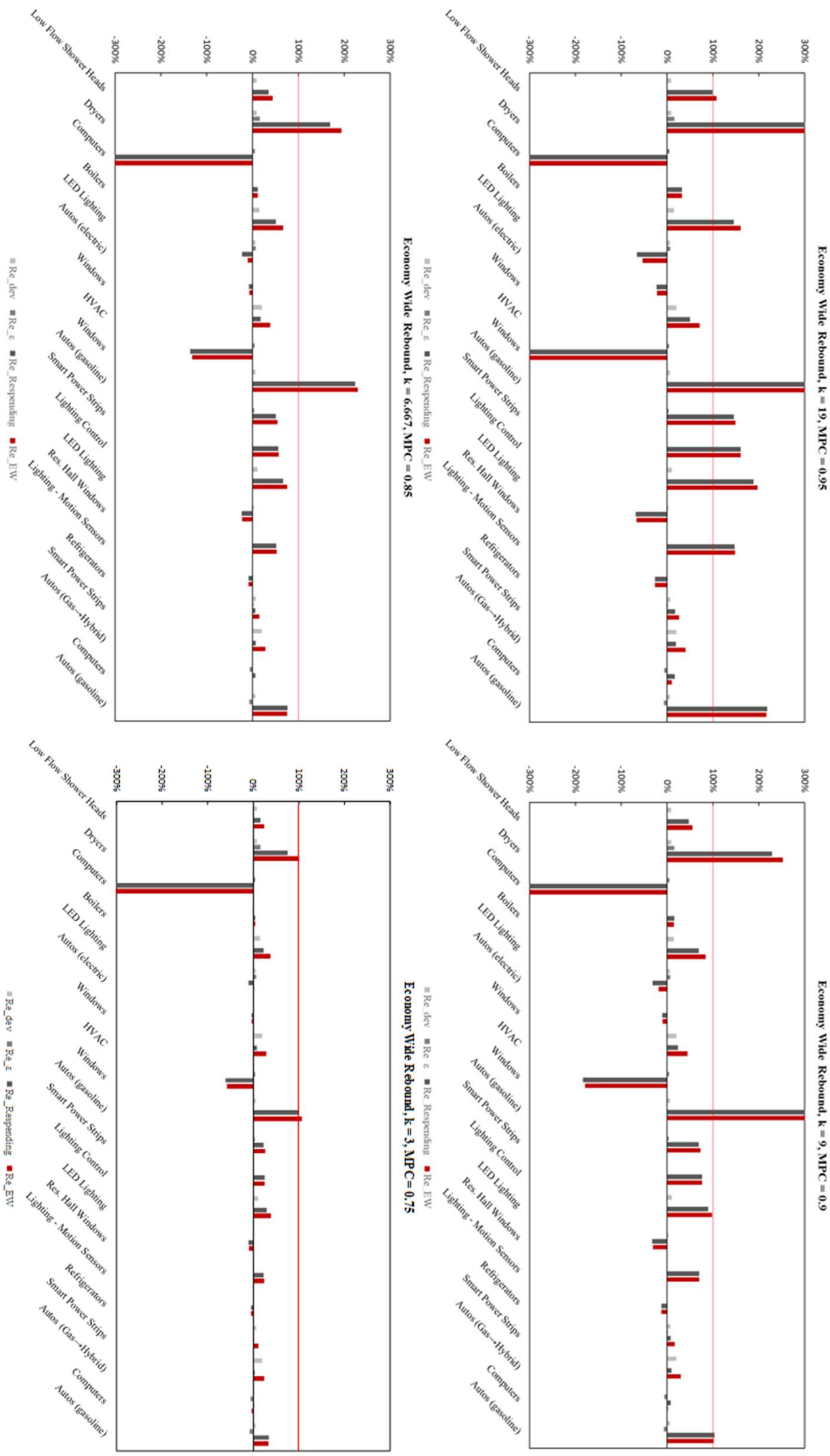

Figure A2. 2: Bar graphs of the sensitivity study for economy wide rebound

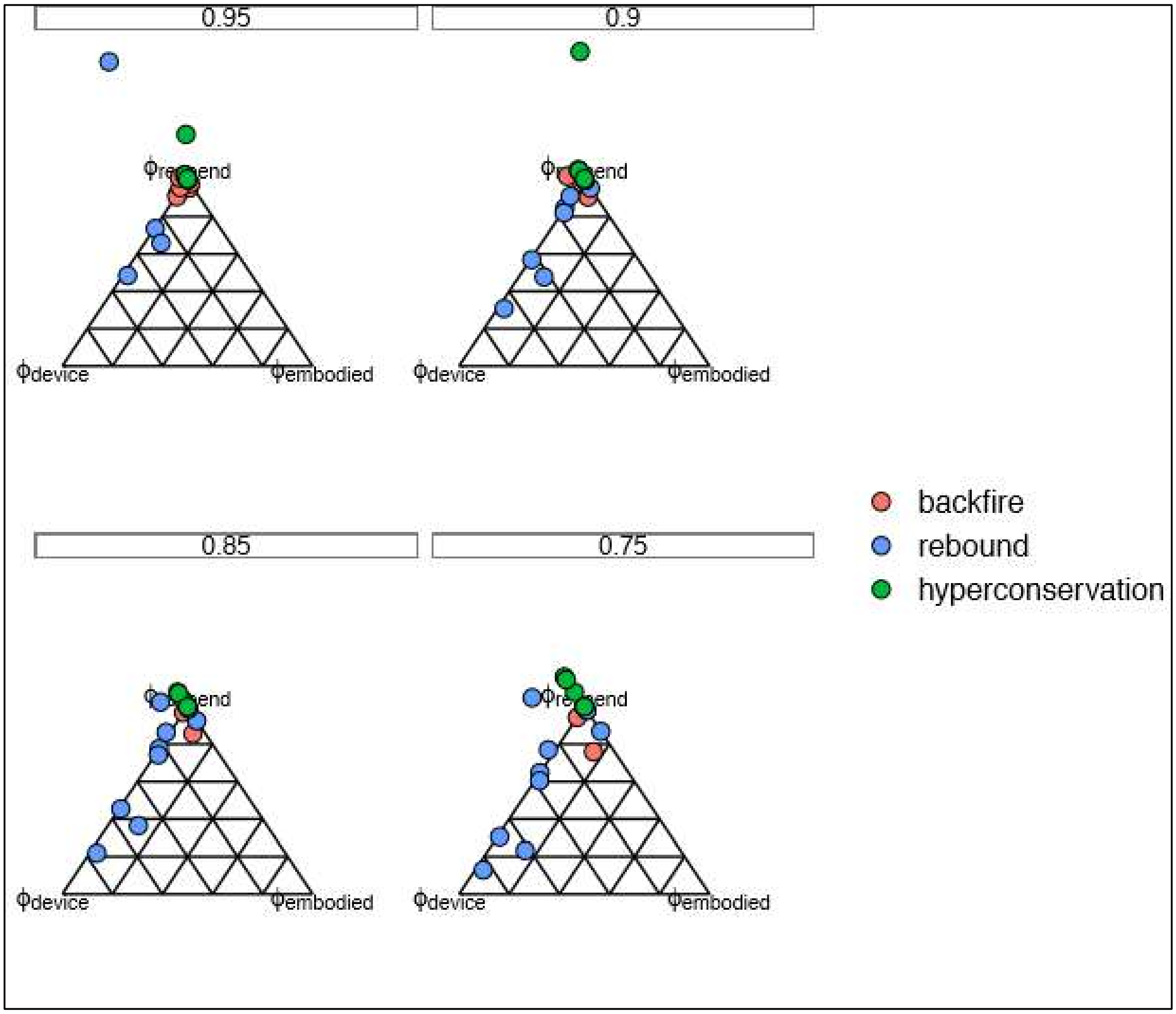

Figure A2. 3: Ternary graphs of the sensitivity study for economy wide rebound. MPC is labeled above each chart.

Executive Appendix A3: Team Wide Sources and Acknowledgements

Sources:

Eia.gov. (2019). U.S. Gasoline and Diesel Retail Prices. [online] Available at: https://www.eia.gov/*dnav*dnav/pet/pet_pri_gnd_dcus_nus_a.htm [Accessed 2 Dec. 2019].

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Mike Troupos from Foresight Energy Management

Appendix B: Low Flow Shower Heads and Dryers

Team 1: Megan Black, Evan Block, Jacob Deysher, and Zach Erickson

Dr. Heun and Dr. Brockway

Engineering 333: Thermal Systems Design

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Introduction

Team 1 focuses on detailing the findings of energy efficiency interventions of the following two cases: low flow shower heads and ENERGY STAR rated dryers. The low flow shower head case is based on the Calvin energy recovery fund (CERF) project where low flow shower heads were implemented in the dorms and KE apartments, tracking water and energy usage and the resulting cost savings. This Calvin-specific case gives an indication of energy rebound at a university-wide level and how this affects the student body. As for the dryers, this appliance often uses more energy than all other household appliances combined (EnergySage 2019), making it a notable source for energy rebound. The following analysis determines the impact of a small-scale intervention (replacing a shower head), and a larger scale intervention (replacing one's dryer).

Methods

Device 1: Low Flow Showers

Research on low flow shower heads comes primarily from the CERF data for the 362 shower heads replaced across Calvin's campus. They collected preliminary data on shower time and shower temperature and projected savings in terms of water usage, sewer costs, and energy savings to the present day. Embodied energies for the showerheads were approximated by finding their weight, assuming them to be solid brass, and dividing by their useful lifetimes. Because showerheads never physically wear out, their lifetimes were assumed to be five years for the sake of analysis. To determine device-level rebound, a function of energy savings, direct energy usage was calculated from the CERF average shower time and an extrapolated increase in shower time in correlation with a European study performed on flow restrictors (Ableitner 2016). See Equations B.1 and B.2 below.

$$\dot{E}_{sav,dev,dir,expected} = \dot{E}_{base,ave\ shower\ time} - \dot{E}_{EE,ave\ shower\ time} \quad \text{(Equation B. 1)}$$

$$\dot{E}_{sav,dev,dir,actual} = \dot{E}_{base,new\ shower\ time} - \dot{E}_{EE,ave\ shower\ time} \quad \text{(Equation B. 2)}$$

The cost of implementation equation was also adjusted for shower heads to include cost of water and sewer. See Equation B.3 below.

$$\dot{C}_{repl} = \frac{C}{\Delta t} + \dot{C}_{water} + \dot{C}_{sewer} \quad \text{(Equation B. 3)}$$

Device 2: Dryers

Several studies were used to evaluate dryer data. The base case and energy efficient case were chosen based on their combined energy factor (CEF) ratings, see Equation B.4 below.

$$CEF = \frac{load\ size\ (lb)}{E_{active} + E_{idle}} \quad \text{(Equation B. 4)}$$

The lowest CEF dryer was chosen as the base case, and then a model with the same dryer drum size, higher CEF rating, and ENERGY STAR rating criteria was chosen as the energy efficient case. Dryer manuals and their warranties were used to determine their respective embodied energies and useful product lifetimes. Energy usage was estimated from the CEF rating from ENERGY STAR, and the average yearly laundry done (see Equation 4). Average household loads per week and average load size come from actual data provided by ENERGY STAR (ENERGY STAR 2015). Lifetime was estimated using the date that the dryer appeared on the market and comparing 2016 dryer lifetime to that of a 2018 dryer.

Results

Device 1: Low Flow Shower Heads

Shower head analysis resulted in a device-level rebound of 8.55%, which lead to an economy-wide rebound of 108% as shown in Table 1. This large economy level rebound is largely due to a re-spending factor as the energy efficient model enables the user to save a lot of money.

Table B.1: Calculated Results for Low Flow Shower Heads

	Base Case	EE Case	% Change
Lifetime [yr]	5	5	0
E_{emb} [MJ/yr]	1,527	1,170	-31
E_{dir} [MJ/yr]	3,211,361	2,042,437	36
C_{repl} [$/year]	32,157	21,140	-52
Price of Energy [$/MJ]	$0.004		
ε [-]	-0.0003		
ϒ [-]	-2.156		
Re_{dev} [%]	8.5		
Re_{Ew} [%]	108		

Table B.2: Low Flow Shower Heads Contribution to Energy-Wide Rebound Effect

Rebound Terms	Re [%]	Φ [-]
Device	8.5	0.079
Embodied	0.0	0.000
Respending	99.2	0.921
Economy Wide	108	1

Device 2: Dryers

Dryer analysis resulted in a device-level rebound of 8.4%, which lead to an economy-wide rebound of 507% as shown in Table 3. This economy level rebound is again largely due to the re-spending factor as a significant amount of energy is saved through these dryers thus causing a large customer re-spending.

Table B.3: Calculated Results for Dryers

	Base Case	EE Case	% Change
Lifetime [yr]	10	15	33
E_{emb} [MJ/yr]	94	186	49
E_{dir} [MJ/yr]	2,382	1,800	24
C_{repl} [$/year]	100	83	-20
Price of Energy [$/MJ]	$0.040		
ε [-]	0.1576		
ϒ [-]	-0.716		
Re_{dev} [%]	8.4		
Re_{Ew} [%]	507		

Table B.4: Dryers Contribution to Energy-Wide Rebound Effect

	Re [%]	Φ [-]
Device	8.4	0.017
Embodied	15.8	0.031
Respending	482.5	0.952
Economy Wide	507	1

Analysis

Device 1: Low Flow Shower Heads

The data from CERF and subsequent calculations demonstrate that low-flow showerheads use less water, less sewage, and less natural gas, saving money overall. Even though the calculations show that people could be taking slightly longer showers with the low-flow models, the resulting device-level rebound is small making its effect basically negligible at this lower level. The rebound from the embodied energy is also negligible since the models are both similar in size and expected lifespan. This is beneficial to the user because it means one does not need to overcome any additional energy usage that may have went into the production of the device. The only significant rebound from low-flow showerheads comes from the re-spending effect. Although this result indicates that the re-spending is highly multiplied through the economy, our case is a Calvin-specific case where all energy savings are put back into energy saving projects here on campus.

Device 2: Dryers

The analysis performed on the two chosen dryers demonstrates that an energy efficient dryer, while costing more and involving more embodied energy, will use less energy over its lifetime. The device-level rebound for this device is small making its effect negligible like that of the low flow shower heads. Because of the longer device lifetime, the energy efficient dryer resulted in a comparable embodied energy to that of the base case making the embodied energy term also negligible. The term that carried the most impact in the economy rebound was the re-spending term. This indicates that although small at the device-level, the energy rebound multiplied through the economy is large, meaning this expected energy saving intervention does not result in any energy savings when analyzed globally.

Conclusion

Although the upfront costs are high, there are notable cost savings when implementing energy efficient models of showerheads and dryers. Any extra purchase costs and increased embodied energies from energy efficient devices are outweighed by water and/or energy savings over their lifetimes. Based on the previous analysis, the energy rebound at the device level for both cases are negligible, meaning that the behaviors of the individual consumers are unlikely to change drastically enough as to negate the cost and energy savings brought on by these energy saving interventions. The low embodied terms demonstrate that manufacturing plays little effect in device backfire. With re-spending as the dominating factor for both devices, money saved by these devices contribute highly to economy-wide energy rebound causing further energy use and carbon emissions. Therefore, these results show positive energy saving impacts individually but have significant potential for high economy-wide energy backfire if savings are not reinvested back into more energy saving solutions.

Appendix B1: Model Numbers and Basic Data for Case Studies

Figure B1. 1: Base Case Model #: LASCO 08-2305 Adjustable Chatham

Figure B1. 2: Energy Efficient Model #: PlumBest Deluxe Shower Head S01-008

Figure B1. 3: Base Case Model #: Whirlpool WED75HEFW

Figure B1. 4: Energy Efficient Model #: Whirlpool YWHD560CH

Table B1.1: Basic Data and Assumptions for the EE and Base Case Low Flow Shower Heads

Basic Data/Assumptions	EE Case	Base Case
Cost of Model [$]	32.53	36.20
Mass [kg]	0.26	0.34
Expected Life [yr]	5	5
Number of Shower Heads Replaced at Calvin [-]	362	362
Ave. Shower Time [min]	7.34	6.92
Cost of Water [$/gal]	0.00238	0.00238
Cost of Sewer [$/gal]	0.00441	0.00441
Cost of Natural Gas [$/MJ]	0.004	0.004

Table B1.2: Basic Data and Assumptions for the EE and Base Case Dryers

Basic Data/Assumptions	EE Case	Base Case
Cost of Model [$]	1000	1250
CEF [lb/kWhr]	5.2	3.93
Mass [lb]	198	177.39
Expected Life [yr]	15	10
Expected Annual Energy Use [kWhr/yr]	460	608
Cost of Electricity [$/MJ]	0.04	0.04
Average Weekly Laundry Load Size [lb/wk]	46	45.95

Appendix B2: Low Flow Shower Head CERF Data

CERF Data - TPT Shower Head Excel Sheet

Cost Savings	$73,427.59
CO2 Savings (metric tons)	269.25
Heating Savings (MMBtu)	5,080.17
Water Savings (gal)	7,290,335.38
Avg. Water Monthly Savings	113,911.49
Avg. Monthly Cost Savings	$1,147.31
Avg. Monthly CO2 (metric tons)	4.21
Avg. Natural Gas Savings (MMBtu)	79.38
Years Monitored	5.33

CERF - Low Flow Shower Heads Excel Sheet

Table 9: List of parameters for calculating savings			
Daily Water Savings [gal] (2013 replacements)	2,697		
Daily Water Savings [gal] (W/ 2014 replaceme	5,149		
Daily Water Savings [gal] (W/ KE Extension)	6,293		
Dorms w/ 7 min shower time	4,918		
KE w/ 7 min shower time [gal/day???]	6,082	14-15 Rates	-18 Rates
Water Cost [$/gal]	$0.00238	0.002317	0.00395
Sewer Cost [$/gal]	$0.00441	0.004336	0.0047
Cold Water Temp [°F]	48		
Hot Water Temp [°F]	128		
Typical Shower Temperature [°F]	106		
Old Flow Rate [gal/min]	1.65		
New Flow Rate [gal/min]	0.93		
Current Gas Rate [$/Mcf]	$5.21		
Number of Showers per Day	4		
Average Shower Time [min]	7.33		
Heat Capacity of Water @ 90F [Btu/lbmF]	0.998		
Density of Water @ 90F [lbm/ft^3]	62.11		
Boiler Efficiency	0.91		
Hot Water Usage Percentage [(Tsh-Tc)/ΔT]	0.725		

Number of Shower Heads	362

Base Case (Old Model)

Water Cost [$/gal]	$0.00238
Sewer Cost [$/gal]	$0.00441
Old Flow Rate [gal/min]	1.65
Total Water Cost per Year [$/yr]	$10,347.02
Total Sewer Cost per Year [$/yr]	$19,189.17
Water Usage [gal/wk]	362,443
Water Usage [gal/yr]	4,349,314
Heat [MMBtu/yr]	3043.78
Heat [MJ/yr]	3,211,361

EE Case (New Model)

Water Cost [$/gal]	$0.00238
Sewer Cost [$/gal]	$0.00441
New Flow Rate [gal/min]	0.93
Total Water Cost per Year [$/yr]	$6,580.74
Total Sewer Cost per Year [$/yr]	$12,204.38
Water Usage [gal/wk]	230,515
Water Usage [gal/yr]	2,766,179
Heat [MMBtu/yr]	1935.86
Heat [MJ/yr]	2,042,437

Figure B2. 1: Snip of CERF Data used for rebound analysis for the energy efficient case.

CERF Data - TPT Shower Head Excel Sheet

Cost Savings	$73,427.59
CO2 Savings (metric tons)	269.25
Heating Savings (MMBtu)	5,080.17
Water Savings (gal)	7,290,335.38
Avg. Water Monthly Savings	113,911.49
Avg. Monthly Cost Savings	$1,147.31
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Water Cost [$/gal]	$0.00238	0.002317	0.00395
Sewer Cost [$/gal]	$0.00441	0.004336	0.0047
Cold Water Temp [°F]	48		
Hot Water Temp [°F]	128		
Typical Shower Temperature [°F]	106		
Old Flow Rate [gal/min]	1.65		
New Flow Rate [gal/min]	0.93		
Current Gas Rate [$/MJ]	$5.21		
Number of Showers per Day	4		
Average Shower Time [min]	7.346		
Heat Capacity of Water @ 90F [Btu/lbmF]	0.998		
Density of Water @ 90F [lbm/ft^3]	62.11		
Boiler Efficiency	0.91		
Hot Water Usage Percentage [(Tsh-Tc)/ΔT]	0.725		

Shower Time

Ave shower time old [min]	6.916735
Ave shower time new [min]	7.346
# showers per day	4
# shower heads replaced	362
School Wide Shower Time Old [min/day]	10015.43228
Schoole Wide Shower Time New [min/day]	10637.008

Old Model

Old Flow Rate [gal/min]	1.65
School Wide Shower Time [min/day]	10,015
# school days [day/yr]	255
Water Usage [gal/yr]	4213993.132
Heat [MMBtu/yr]	2949.08
Heat [MJ/yr]	3,111,445.70

New Model

Heat [MJ/yr]	2,042,437.24

Figure B2. 2: Snip of CERF Data used for rebound analysis of the old model shower head.

Appendix B3: Energy Efficient Low Flow Shower Head Rebound Analysis

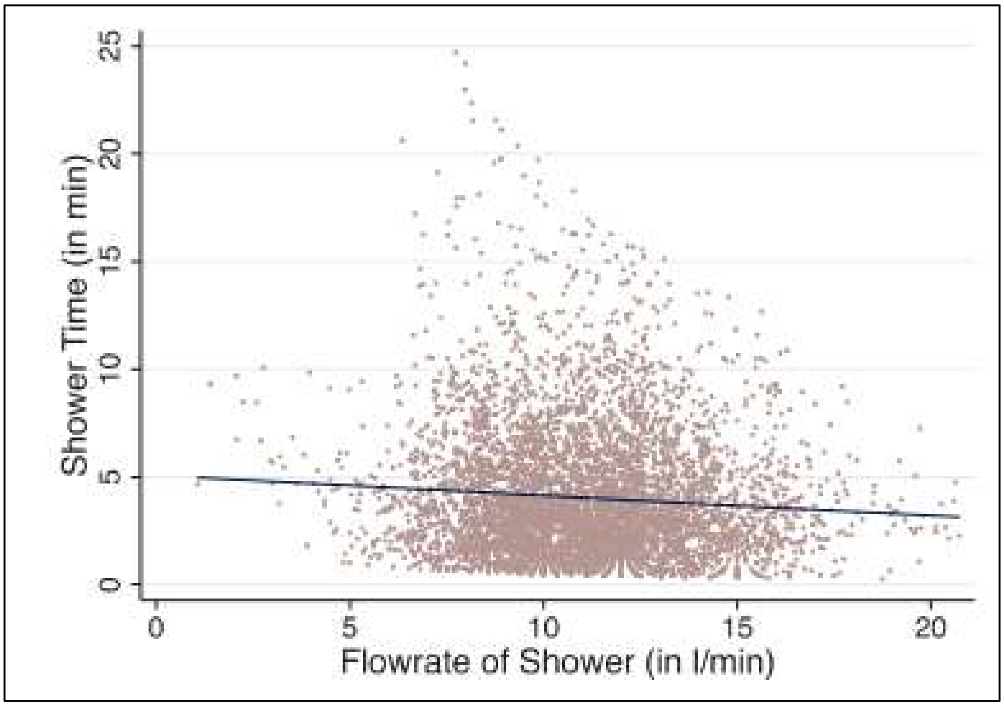

Figure B3. 1: Graph used to help verify shower time for rebound analysis.

Table B3. 1: Extrapolation from researched article to CERF shower time.

Article	
Average shower time (min)	4
Water saved (gal/min)	0.26
Time increased (min)	0.09
CERF	
Average shower time (min)	7
Water saved (gal/min)	0.72
Time increased (min)	0.43

Energy Efficient Case

Device Data/Assumptions

	Value	Source
Model #	PlumBest Deluxe Shower Head Part # S01-008	CERF
Expected Life time [yrs]	5	shower head store
Mass [kg]	0.261	Actaul value from scale
Number of Shower Heads	362	CERF

Embodied Energy

	Value	Source
Embodied Energy Factor - Brass [MJ/kg]	62	ee-coefficients.pdf
E_emb [MJ/yr]	1169.87	NA

Cost of Replacement

	Value	Source
Cost of Model [$]	$32.53	Amaozn
Number of Shower Heads	362	CERF
Expecetd Life [yr]	5	shower head store
Cost of Water [$/yr]	$6,580.74	CERF
Cost of Sewer [$/yr]	$12,204.38	CERF
C_repl [$/yr]	21,140.30	NA

Direct Energy Use

	Value	Source
E_dir_expected [MJ/yr]	2,042,437.24	CERF
E_dir_actual [MJ/yr]	2,042,437	CERF

Figure B3. 2: EE Low Flow Shower Head data showing different values as part of the rebound calculations.

Appendix B4: Old Model Low Flow Shower Head Rebound Analysis

Base Case

Device Data/Assumptions

	Value	Source
Model #	LASCO 08-2305 Adjustable Chatham	CERF
Expected Life time [yrs]	5	shower head store
Mass [kg]	0.340	Amazon
Number of Shower Heads	362	CERF

Embodied Energy

	Value	Source
Embodied Energy Factor - Brass [MJ/kg]	62	ee-coefficients.pdf
E_emb [MJ/yr]	1527.06	NA

Cost of Replacement

	Value	Source
Cost of Model [$]	$36.20	Amaozn
Number of Shower Heads	362	CERF
Expecetd Life [yr]	5	shower head store
Cost of Water [$/yr]	$10,347.02	CERF
Cost of Sewer [$/yr]	$19,189.17	CERF
C_repl [$/yr]	32,157.07	NA

Direct Energy Use

	Value	Source
E_dir_expected [MJ/yr]	3,211,361.29	CERF
E_dir_actual [MJ/yr]	3,111,446	*Quantifying the Potential of Voluntary Energy Efficiency Measures: The Case of Flow Restrictors*

Figure B4. 1: Old Model Low Flow Shower Head data showing different values as part of the rebound calculations.

Device Level Rebound

	Value
E_save_dir_expected [MJ/yr}	1,168,924
E_save_dir_actual [MJ/yr]	1,069,008.47
Re_dev [%]	8.548%

Figure B4. 2: Device-level Rebound Data for Old Model Low Flow Shower Heads.

Appendix B5: Dryer Analysis

Embodied Energy Total for Whirlpool YWED75HEFW							
944.1978 MJ							
	Top and Console Parts						
Diagram #	Part #	Description	Price	Material	Weight (lbs)	Weight (kg)	Eemb
1	W10804688	Use And Care Guide		Paper	0.01	0.00453592	0.057153
2	WPW102 08383	Top (white) (Replaces: W10208383)	$108.84	Steel	7.3	3.3112216	33.44334
3	W106375 39	Harness, Wiring (main)	$92.31	Copper	1.24	0.56245408	39.70926
4	WPW103 01510	Panel, Console (white) (Replaces:	$61.61				

Figure B5. 1: Snip of Data used to determine Embodied Energy for our dryers. It required using a list of all the parts and the weights and using the embodied energy coefficients to calculate the overall embodied energy.

Material For EE Case		lbs	kg	EMB MJ
Paper		1	0.453592	5.715259
Steel		155.388	70.48275	711.8758
Plastic		35.612	16.15332	1793.018
Rubber		5.016	2.275217	250.2739
Brass		0.984	0.446335	31.51122
Total Weight	Weight	198	89.81122	2792.395
	Weight	86.1826 kg		
	EMB Total (MJ)	2792.395		

Figure B5. 2: Snip of the Embodied Energy Calculation for the EE dryer case.

Model: Whirlpool YWED75HEFW (Lowest CEF rating on Energy STAR)	
Type	Electric
Height (in)	38
Width (in)	27
Depth (in)	31
CEF (lb/kWhr)	3.93
Annual Energy Use (kWh/yr)	608
Energy Test Cycle Time (min)	73
Meets ENERGY STAR most efficient	NO
Cost ($)	1000

Figure B5. 3: Old Model Dryer Data.

Model: Whirlpool YWHD560CH	
Type	Electric
Height (in)	38
Width (in)	27
Depth (in)	31
CEF (lb/kWhr)	5.2
Annual Energy Use (kWh/yr)	460
Energy Test Cycle Time (min)	70
Meets ENERGY STAR most efficient	YES
Cost ($)	1250

Figure B5. 4: EE Dryer Model Data.

	EE Case	Base Case
	YWHD560CH	YWED75HEFW
E_dot direct actual (MJ/yr)	1656	2,189
E_dot direct expected (MJ/yr)	1,800	2,382
$Re_{Device\ Level}$	8.4%	
Lifetime (yr)	15	10
C_{repl} ($)	1250	1000
labor ($/yr)		
C_dot_{repl} ($/yr)	83.33	100.00
Mass (lb)	198	177.39
Plastic (%)		
Steel (%)		
Recycled Material (%)		
Recyclable Material (%)		
E_dot_emb (MJ)	2792.395	944.198
E_dot_emb (MJ/yr)	186.16	94.42

Figure B5. 5: More data for EE and Base Case Dryer Models.

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Appendix C: Computers and Boilers

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Engineering 333: Thermal Systems Design

December 18, 2019

Introduction

Team 2 focused on two specific energy interventions. The first denoted throughout the body of this appendix as *Device 1: Boiler* is an industrial boiler for space heating on Calvin's campus. In this case the existing Hurst 400 series boiler was considered the base case and was to be replaced with the energy efficient Burnham 4S-500. Figure C.1 shows these two models.

The second device is denoted as *Device 2: Rack Servers* and represents the replacement of industrial servers. In this case the Dell PowerEdge R710 represents the base case and this was to be replaced with the Dell PowerEdge R720 which was considered the Energy Efficient case. Figure C.2 shows these two models.

Figure C.1: The base case boiler and efficient case boilers.

Figure C.2: The R720 Server

Methods

Device 1: Boilers

Direct Energy Consumption

The direct energy consumption was found for the base case boiler by utilizing research from past Engr-333 projects. The annual natural gas use by the Calvin's Main Power Loop was found for the year of 2017 and it was assumed that the natural gas usage was similar for each year since that project. Calvin currently has 6 boilers that are running: 2 in Commons dining hall, 2 in Knollcrest dining hall, and 2 in the Science Building heating facility. The Calvin Physical plant does not keep records on how much natural gas each boiler consumes; therefore, a method for estimating the natural gas consumption of one of the Hurst boilers in the Science Building complex had to be devised. Each of the 6 boilers on campus were visited and the boiler specifications were recorded as shown in Table 1A in Appendix B. (Engineering 333 Section B, 2017). The percentage of the annual natural gas used by each boiler was then scaled by the output potential of that boiler to get the annual energy usage for each boiler on campus including the base case. In actuality, the more efficient boilers are run at full power and the less efficient boilers are used when needed. Since the weighted potential method results in the more efficient Hurst boilers contributing the most to total heating, the method was assumed to be close to the actual value. These calculations are shown in Appendix B. The energy usage of the efficient case calculated from the efficiencies of the boilers as shown in Equation 1.

$$\dot{E}_{dir_{ee}} = \dot{E}_{dir_{base}} \frac{\eta_{base}}{\eta_{ee}} \qquad \text{(Equation C. 1)}$$

In this equation, η_i, refers to the efficiency of the boiler and $E_{dir,i}$ refers to the direct energy usage by each boiler in MJ/yr. The calculations for direct energy are shown in Appendix B.

Embodied Energy Consumption

The embodied energy of each of the boilers was calculated by estimating the mass of each material in the device and multiplying the mass by the energy required to process a unit mass of each material. Since the boilers are primarily made of steel, the embodied energy was calculated assuming the entire boiler was steel (B Coffee 2019, personal communication, 27 September). The other materials in a boiler are negligible amounts of cement, plastic, and other metals such as aluminum, therefore, this assumption results in a conservative, but accurate estimate for the embodied energy for the materials (Koubogiannis, 2016, p.5). This estimate was verified by using the mass percentages from a medium-sized boiler to find the embodied energy which resulted in a slightly lower embodied energy. The mass of each boiler was found from specification sheets provided by the manufacturer (Burnham Commercial Boilers, 2015; Hurst Boiler Company. 2014). According to a Hurst representative, the embodied energy associated with manufacturing the base case or efficient boiler was not documented. Therefore, the embodied energy associated with manufacturing the boiler was assumed to be 20% of the material embodied energy since steel has a relatively high embodied energy per unit mass (M Heun 2019, personal communication, 20 October). The following equation was used to determine the total embodied energy for each boiler:

$$\dot{E}_{emb,i} = 1.2\left(\frac{E_{emb,materials,i}}{t_{lifecycle}}\right) \qquad \text{(Equation C. 2)}$$

In this equation, $E_{emb,materials,i}$ refers to the embodied energy of steel in the boilers in MJ and $t_{lifecycle}$ is the economic lifecycle of each boiler in years.

Cost of Replacement

The cost of replacement for each of the boilers was calculated by determining the purchase cost of equipment, installation cost, maintenance cost, and disposal cost for each boiler and dividing the sum of the costs by the lifecycle of the device. The purchase cost of equipment was found by contacting Hurst Boilers for the base case and contacting a Burnham boiler distributor, RL Deppmann, for the efficient case (RL Deppmann, 2019). Quotes were received for both devices and the installation cost were assumed to be included in the quotes (T Kolk 2019, personal communication, 17 October). The maintenance costs for a commercial packaged boiler was determined from past Engr-333 projects (Engineering 333 Class, 2015). Not much information is recorded on the disposal cost of industrial boilers; thus, it was difficult to conduct research in this area. The disposal was assumed to be similar in magnitude to the amount needed to install it; therefore, the installation cost from the same Engr-333 project as listed previously was taken to be an estimate for the disposal cost. The Energy Technology Systems Analysis Programme estimates an industrial boiler life expectancy of 20-40+ years (Vanwortswinkel, 2010). It was estimated that the boilers in this study would have an economic lifecycle of 40 years since that is the upper limit of what was reported. Some of the Kewanee boilers on Calvin's campus are more than 60 years old, but there is no way of knowing whether the boilers in this study would be maintained that long. The cost of replacement for each boiler was calculated using the following equation:

$$\dot{C}_{repl,i} = \frac{C_{purchase} + C_{installation} + C_{disposal}}{t_{lifecycle}} + \dot{C}_{OM} \qquad \text{(Equation C. 3)}$$

In this equation, C_i refers to the cost component in U.S. dollars ($) and $\dot{C}_{OM}$ refers to the annual cost of operations and maintenance in $/yr.

Device 2: Rack Servers

Direct Energy Consumption

A direct comparison of the energy consumption of the two models at 85% utilization was done by the industry reviewer, Principled Technologies (2009, Figure 7). As the two models had different efficiencies, their energy consumption ($E_{dir,i}$) had to be pro-rated using the equation:

$$E_{dir,ee} = E_{dir,base}\left(\frac{\eta_{base}}{\eta_{ee}}\right) \qquad \text{(Equation C. 4)}$$

In this equation, η_i refers to the efficiency of a server, in terms of performance/watt. This performance was not a standard measure of performance, such as SSJ operations. Instead, the performance per watt for each model was directly given in the comparison done by Principled Technologies.

Although the energy consumption rates were originally given in [W], they had to be converted to [MJ/yr] to correspond to the theoretical equations. Assumptions had to be made about the percentage of time the servers would be running at 85% utilization rate. For simplicity, it was assumed that the servers would be running continuously throughout a year, that is, 61320 seconds per year.

Embodied energy consumption

To calculate the embodied energy consumption rate of each model, the embodied energy required for manufacturing was calculated based off published results from Dell on the greenhouse gas emissions associated with the production of each model (Stutz, 2013, Figure 3).

To convert these metrics from GHG emissions to energy consumption, the emissions intensity of electricity production in China was used (Jian, 2019, Table 7), as Dell has a computer manufacturing plant there (Dow Jones, 1998). The equation used to do this was:

$$E_{emb,i} = GHG_i(EF_{elec}) \qquad \text{(Equation C. 5)}$$

In this equation, the subscript "i" refers to the server type (Base or EE). GHG_i refers to the greenhouse gas emissions associated with the manufacturing of the server, and EF_{elec} was the emissions factor, listed in units of tonsCO_2Eq/tonsCoalEq. This number had to be converted to MJ/yr, which required that a server lifetime be estimated. The server lifetimes used are shown in Table 3 and are taken from the study done by Principled Technologies.

Cost of Replacement

The purchased equipment cost of the energy efficient case was obtained from the Principled Technologies study, as well as Operations and Maintenance costs for both cases. The purchased equipment cost of the base case had to be estimated. In a study by Jonathan G. Koomey et. Al, (2009) relations between server cost and various performance parameters were related.

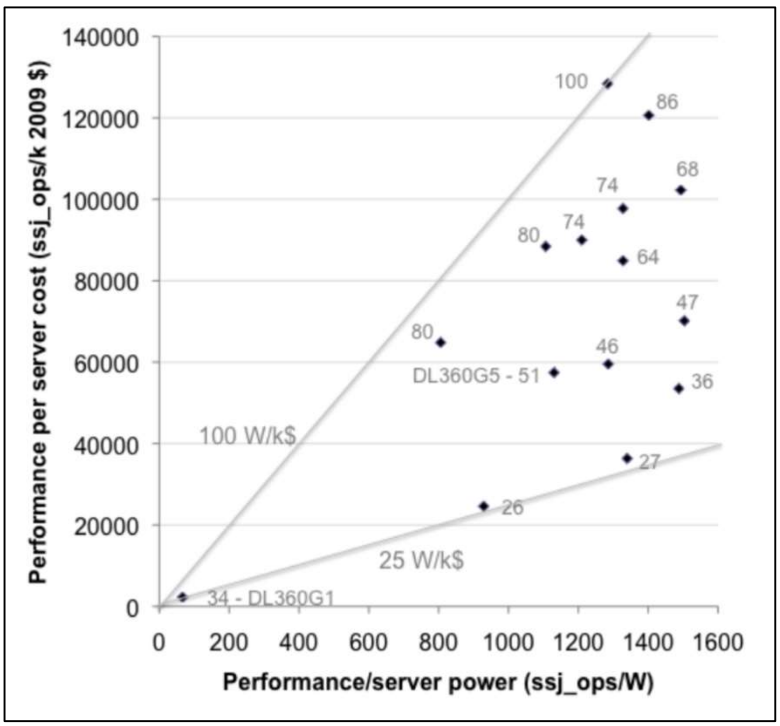

Figure C. 3: Performance Per Watt and Performance per Kilodollar (from Koomey 2009).

In Figure 3 there is found to be a positive relation between performance-per-watt and performance-per-dollar among various current servers. Performance is measured by the SPECpower_ssj2008 benchmarking tool from the Standard Performance Evaluation Corporation, in which the server is made to run server-side Java at a given volume, and its computation rate is measured. This performance metric is called ssj_ops. In the study, the base case server was not included on the figure, but since SPEC released benchmarking results for the base case server (SPEC, 2009), we could find our server's point on the figure by estimating a regression of all the other server performance benchmarks and costs. We used a line through the origin with a slope of 50 Watts per 2009 kilodollar.

Results

The calculated results for boiler are shown in Table C.1 and the Economy-wide rebound effects are shown in Table C.2. The calculated results for computer servers are shown in Table C.3 and the Economy-wide rebound effects are shown in Table C.4.

Table C. 1: Device 1 Calculation Parameters

	Base Case	EE Case	% Change
Lifetime [yr]	3	3	0
E_{emb} [MJ/yr]	70	108	36
E_{dir} [MJ/yr]	9,066	8,290	9
C_{repl} [$/year]	19,000	20,662	8
Price of Energy [$/MJ]	$0.040		
ε [-]	0.0496		
ϒ [-]	53.517		
Re_{dev} [%]	0.0		
Re_{Ew} [%]	-15,521.3		

Table C. 2: Device 1 Contribution to Energy-Wide Rebound Effect

	Re [%]	Φ [-]
Device	0.0	0.000
Embodied	5.0	0.000
Respending	-15,526.2	1.000
Economy Wide	-15,521.3	1

Table C. 3: Device 2 Calculation Parameters

	Base Case	EE Case	% Change
Lifetime [yr]	40	40	0
E_{emb} [MJ/yr]	16,504	14,936	-10
E_{dir} [MJ/yr]	270,000,000	243,000,000	10
C_{repl} [$/year]	7,625	8,801	13
Price of Energy [$/MJ]	$0.004		
ε [-]	-0.0001		
ϒ [-]	0.010		
Re_{dev} [%]	0.0		
Re_{Ew} [%]	32		

Table C. 4: Device 2 Contribution to Energy-Wide Rebound

	Re [%]	Φ [-]
Device	0.0	0.000
Embodied	0.0	0.000
Respending	32.0	1.000
Economy Wide	32	1

Analysis

Device 1: Boilers

The economy-wide rebound of the implementation of a more efficient water heating boiler at Calvin University is 32%. This indicates that investing in a more efficient space and water heating boiler will result in less energy saving than what would be expected from the energy savings. This reduction in energy savings it mostly due to the rebound associated with the re-spending effect which is represented quantitatively by $Re_{respend}$. The rebound associated with the re-spending effect, $Re_{respend}$, for boilers was approximately 32%. This indicates that the money saved from the efficiency of the new boiler would be respent in other parts of the economy and would thus result in less energy saving than one would expect.

The rebound associated with the energy savings embodied in the devices, Re_{emb}, was negative (-0.006%). Re_{emb} is negative since there are energy saving directly from the efficiency of the device. Because the efficient boiler consumes less energy than the base case to provide the same amount of heating, the rebound is negative. The Re_{emb} value has very little effect on the economy-wide rebound since it is so small. This is because the boilers consume so much more energy than is required to manufacture the each of the boilers.

Finally, the device-level rebound, Re_{dev}, is 0% in the case of boilers since the usage of industrial boilers is dictated by the managers of the company or institution that utilizes them (Friedman, 2016). It is unlikely that the manager of the boilers would run the boilers longer or at a higher rate of output since space and water heating is fixed-value requirement. This means that the users of the boiler products will require a set amount of it, regardless of how much it costs to obtain the products. Therefore, the boilers will be used for as much as they are needed regardless of energy savings.

Since all the rebound variables are either zero or close to zero, the rebound of industrial boilers is dictated by the spending constants in the theory equation. Therefore, for any device that has a very large energy usage cost compared to the initial cost and embodied energy and a negligible device-level rebound, the economy-wide rebound would most likely be similar to the value for obtained for industrial boilers.

Device 2: Rack Servers

The economy-wide rebound of the conversion to energy efficient rack servers is negative (-155.2%). This indicates that investing in energy efficient servers significantly reduces the total energy consumption. Because the energy efficient case is so much more expensive, energy savings are accrued by drawing money out of the economy and preventing the re-spending effect. This prevention of the re-spending effect contributes the most to the magnitude of the economy-wide rebound, as shown by the value of $Re_{respend}$, which is over 100%.

The embodied energy rebound, Re_{emb}, is negative in this case, because it is causing rebound in a different "direction" than Re_{EW}. That is, more embodied energy is being used in the energy efficient case. This would normally cause a positive rebound. However, since the overall economy-wide rebound is negative, the embodied energy rebound is acting in opposition to the economy value, and so is negative.

Metaphor: What does a negative rebound mean? Consider this scenario. You have the option to buy an inexpensive home and travel more, or to buy an expensive home and be more stationary. In the case that you buy the inexpensive home, you may be using more natural gas to heat your home, as well as more jet fuel and gasoline to travel. If you buy the more expensive home, you might have better insulation and so use less natural gas for heating, and you would not have the money to travel. The decision to buy a more expensive home would result in a negative economy-wide rebound, because you would be taking money "out" of the economy, thereby reducing re-spending.

The economy-wide rebound of the conversion to energy efficient rack servers is negative. This indicates that investing in energy efficient servers significantly reduces the total energy consumption. This is due to the large contribution of $Re_{respend}$.

Conclusion

Device 1: Boilers

The energy savings due to replacing one of the boilers on the campus of Calvin University is significant in magnitude. The replacement cost for a more efficient boiler would be small compared to the energy cost savings one would see with a more efficient boiler. The assumption made it this report is that the efficiency of the boilers, the annual energy usage, and the cost of energy remains relatively the constant. In reality, the efficiency of the boilers decreases over time. The efficiency of industrial boiler can drop to 68% after 40 years of service (Engineering 333 Class, 2015). Given that both boilers would drop in efficiency, it is unlikely that the economy-wide rebound would change much. This assumption is backed up by a sensitivity study conducted on the energy usage of the boilers. Only once the energy usage dropped by a factor of 2, did the economy-wide rebound change by a whole percent. The annual energy usage would not fluctuate that much from year-to-year unless if there was an unprecedented cold or hot season. As global temperatures rise, there may be a decrease in the amount of energy used for heating. Given the lifetime of the boilers in question, this slight change in energy usage per year would not appreciably change the economy-wide rebound figure. Further research might investigate the expected changes in seasonal temperatures on energy usage as well as the effect of possible increased natural gas prices in the future. Since one would assume that inflation would affect the price of both boilers in the same way, the total economy-wide rebound would remain close to the value that was determined from this research.

Device 2: Rack Servers

The improvement of server efficiency appears to be fairly effective in saving energy at the device-level. It is important to note that the computation load is assumed to be the same for both the energy efficient server and the base case server. However, it seems that at a macro scale this may not hold true. While the computation load of a given server may not change if a small business replaces one server with another, the computation load required by servers nationwide is growing quickly. In the United States Data Center Energy Usage Report by Arman Shehabi et al. (2016, p ES-2), it is noted that "the combination of these efficiency trends as resulted in a relatively steady U.S. data center electricity demand over the past 5 years, with little growth expected for the remainder of this decade. It is important to note that this near constant electricity demand is occurring while simultaneously meeting a drastic increase in demand for data center services." The study estimates that if energy savings efforts were halted in 2010, more than 600 billion kWh would have been required across the 2010's decade. While it is no surprise that computation demand should increase with time, it is possible that this increase is due to the increase of affordability of computation with the increase in efficiency of servers. This study has modeled a server replacement in a small business, where computation is held at a constant, fixed rate between both cases and savings are respent at the average energy intensity of the economy. However, in a data center, wherein computation may not be held constant, savings would likely be used to scale up computation and to lower the price of computation, increasing computation demand. Further study might investigate the effect of average server efficiency on demand for server energy use economy-wide in order to determine the indirect rebound, if any.

Appendix C1: Boiler Calculations.

Table C1. 1: Natural gas usage in Calvin's main power loop.

Month	Natural Gas Purchased (includes inefficiency of boilers)	Units
July 2016	57634.32	cubic ft/month
August 2016	65748.61	cubic ft/month
September 2016	69007.89	cubic ft/month
October 2016	79652.90	cubic ft/month
November 2016	102770.06	cubic ft/month
December 2016	164554.37	cubic ft/month
January 2017	190236.53	cubic ft/month
February 2017	148872.94	cubic ft/month
March 2017	144209.01	cubic ft/month
April 2017	79471.47	cubic ft/month
May 2017	79032.90	cubic ft/month
June 2017	58614.25	cubic ft/month
Total:	**1239805.24**	cubic ft/month

Table C1. 2: Boiler specifications.

Boiler Data			
Boiler:	**Base Case**	**Efficient Case**	Units:
Model #:	55-X-400-125W	4S-500	-
Approx. Weight:	37900	34300	lbs
Approx. Mass:	17191.17	15558.24	kg
Thermal Output:	16,750,000	18,014,000	BTU/hr
Thermal Output:	4908.96	5279.40	kW
Horse Power	500	500	HP
Max Pressure	125	125/130	psi
Efficiency	78	86.6	%
Life-cycle:	40	40	years
Rebound:	0		%

Table C1. 3: Embodied energy calculations for boilers.

Embodied Energy			
Approximate Composition:		Composition Mass of Base [kg]	Emb E Composition Base [MJ]
Steel:	0.941	16176.89	550117.48
Embodied Energy [MJ/kg]		Manufacturing Energy [MJ]	110023.50
Steel:	32	**Total Emb Energy Base [MJ/yr]:**	16503.52
		Composition Mass of EE [kg]	Emb E Composition EE [MJ]
		14640.30	497863.58
		Manufacturing Energy [MJ]	99572.72
		Total Emb Energy EE [MJ/yr]:	14935.91

Table C1. 4: Direct energy consumption calculations for boilers.

Energy Consumption			
Energy in a ccf of Nat. Gas	943,213.30	943,213.30	BTU/ccf
Campus Nat. Gas Usage	1239805.242	1239805.242	ccf/yr
Campus Nat. Gas Usage	1.1694E+12	1.1694E+12	BTU/yr
Campus Nat. Gas Usage	1,233,783,308.03	1,233,783,308.03	MJ/yr
Nat. Gas Usage per boiler	205,630,551.34	205,630,551.34	MJ/yr
Direct Energy Consumption	2.70E+08	2.43E+08	MJ/yr

	Max Output:	Units:	Percent	Fraction	Usage
Commons Boiler 1	14525	MBH	18.98%	5.26767642	234,217,748
Commons Boiler 2	14524	MBH	18.98%	5.268039108	234,201,623
Knollcrest Boiler 1	6982	MBH	9.13%	10.95860785	112,585,770
Knollcrest Boiler 2	6982	MBH	9.13%	10.95860785	112,585,770
SB Boiler 1	16750	MBH	21.89%	4.567940299	270,096,198
SB Boiler 2	16750	MBH	21.89%	4.567940299	270,096,198
Total	76513	MBH			

Table C1. 5: Cost calculations for the boilers.

Costs		
	Base Case	Eff. Case
Initial Cost	$ 148,000.00	$ 195,052.00
Installation Cost	Included	Included
Maintenance Costs [$/yr]	$ 3,800.00	$ 3,800.00
Disposal Cost	$ 5,000.00	$ 5,000.00
Total:	$ 305,000.00	$ 352,052.00
C_{repl} [$/yr]	$ 7,625.00	$ 8,801.30

Table C1. 6: Sensitivity study on boiler natural gas usage.

Re_EW	Energy Usage BC	Energy Usage EE	E_sav_exp	epsilon	gamma
0.31	70,000,000.00	63,048,498.85	6,951,501	-2.26E-04	0.0387139
0.31	90,000,000.00	81,062,355.66	8,937,644	-1.75E-04	0.0301108
0.31	110,000,000.00	99,076,212.47	10,923,788	-1.44E-04	0.0246361
0.32	130,000,000.00	117,090,069.28	12,909,931	-1.21E-04	0.0208459
0.32	150,000,000.00	135,103,926.10	14,896,074	-1.05E-04	0.0180665
0.32	170,000,000.00	153,117,782.91	16,882,217	-9.29E-05	0.0159410
0.32	190,000,000.00	171,131,639.72	18,868,360	-8.31E-05	0.0142630
0.32	210,000,000.00	189,145,496.54	20,854,503	-7.52E-05	0.0129046
0.32	230,000,000.00	207,159,353.35	22,840,647	-6.86E-05	0.0117825
0.32	250,000,000.00	225,173,210.16	24,826,790	-6.31E-05	0.0108399
0.32	270,000,000.00	243,187,066.97	26,812,933	-5.85E-05	0.0100369
0.32	290,000,000.00	261,200,923.79	28,799,076	-5.44E-05	0.0093447
0.32	310,000,000.00	279,214,780.60	30,785,219	-5.09E-05	0.0087418
0.32	330,000,000.00	297,228,637.41	32,771,363	-4.78E-05	0.0082120
0.32	350,000,000.00	315,242,494.23	34,757,506	-4.51E-05	0.0077428
0.32	370,000,000.00	333,256,351.04	36,743,649	-4.27E-05	0.0073243
0.32	390,000,000.00	351,270,207.85	38,729,792	-4.05E-05	0.0069486
0.32	410,000,000.00	369,284,064.67	40,715,935	-3.85E-05	0.0066097
0.32	430,000,000.00	387,297,921.48	42,702,079	-3.67E-05	0.0063023
0.32	450,000,000.00	405,311,778.29	44,688,222	-3.51E-05	0.0060222
0.32	470,000,000.00	423,325,635.10	46,674,365	-3.36E-05	0.0057659
0.32	490,000,000.00	441,339,491.92	48,660,508	-3.22E-05	0.0055306

Appendix C2: Server Calculations

Table C2. 1: Embodied energy calculations for servers.

Metric	Value	Units
GHG_mfg_base	499	kgCo2eq
GHG_mfg_ee	775	kgCo2eq
Emission Factor of Electricity	5.399	[tCo2/tce]
Energy Conversion Factor	8141	kWh/tce
CO2 Mass Conversion	1000	kg/tonne
Overall conversion	1.507	kWh/kgCO2eq
E_emb_base	751.993	kWh
E_emb_ee	1167.925	kWh
kWh -> MJ Conversion	0.277777778	MJ/kWh
Lifetime	3	years
E_dot_emb_base	**69.6**	**MJ/yr**
E_dot_emb_ee	**108.1**	**MJ/yr**

Table C2. 2: Direct energy calculations for servers.

Metric	Value	Units
Power_base	287.3	W
Power_ee	352.9	W
(Performance/Watt)_base	743.3	Perf/W
(Performance/Watt)_ee	812.9	Perf/W
Conversion	31.556	(MJ/yr) / watt
E_dot_dir_base	**9066.0388**	**MJ/yr**
E_dot_dir_ee	**8289.8**	**MJ/yr**

Table C2. 3: Cost calculations for servers.

Metric	Base Case	EE Case	Units
Model Cost	4986	12509	$
Licensing and software costs	27744	36336	$
Operational Costs	13360	13140	$
Operational Timeline	3	3	Years
C_dot_repl [$/yr]	$ 15,363	$ 20,662	
C_repl [total $]	$ 46,090	$ 61,985	
ssj_ops:	910978		
ssj_ops/W	3923		
(ssj_ops/k$)/(ssj_ops/W)	50	W/k$	
ssj_ops/k$	196150		
Cost in $:	4644.292633		
With inflation:	4985.71		

Appendix C3: Sources

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Appendix D: LED Lighting and Automobiles (Electric)

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Dr. Heun and Dr. Brockway

Engineering 333: Thermal Systems Design

December 18, 2019

Introduction

Two energy efficiency interventions were analyzed to determine their effects on economy-wide rebound. The first device chosen to study was lightbulbs. This energy efficiency intervention involves replacing metal halide lights with LED lights with a higher efficiency. This device was chosen because Calvin implemented this change in its Tennis and Track building (T&T) in 2014. They switched all the old halide lights with LED lights, and they have detailed data collected about costs, energy savings, usage, and more. The team studied the effects of switching all the old metal halide lights with new LED lights rather than looking at a one light to one light switch due to the data that was available from CERF.

The second device chosen to study was switching from a gas car to a hybrid car. The specific models chosen are switching from a 2014 Toyota Corolla (gas) to a 2014 Toyota Prius (hybrid). This topic was chosen due to the team's interest in automobiles and curiosity about the rebound effects of fuel-efficient cars.

Methods

To ultimately calculate the economy-wide rebound effects of implementing each energy efficiency intervention, several variables for each device needed to be found including embodied energy, direct energy consumption, and cost of implementation, and the price of energy. A discussion of how each of these variables were found can be seen below.

Device 1: Lights

Assumptions:

The lifetime of each lighting system was estimated from Calvin Energy Recovery Fund (CERF) data. The lifetime of the LED system was estimated to be 20 years and the lifetime of the metal halide system was estimated to be 4 years.

Embodied Energy:

The embodied energy of each lighting system was estimated. This was done by estimating the embodied energy of one metal halide light and one LED light, and multiplying by the number of lights in each system. The embodied energy for each light was calculated by using mass breakdowns of the LED and the metal halide lights. Mass of the shell was estimated at roughly 50% aluminum and 50% ABS plastic for the face of the light, and the rest of the mass was allocated to copper for the internal wiring of the light. The mass of the metal halide system was done by measuring the size of the parts and then calculating the volume of each shape. The volume was then converted to mass by using the density of each material. The total mass was then converted to embodied energy terms by using a conversion factor from the University of Wellington (University, Victoria Wellington). The total embodied energy of each system was then divided by the estimated life of each system to find an average embodied energy per year. This yielded an embodied energy value of 6,691 [MJ/yr] for the metal halide system and a value of 15,184 [MJ/yr] for the new VHB system.

Direct Energy Consumption:

The amount of electricity paid for by Calvin for lighting the T&T with the metal halide lights was known from CERF data. Base case direct energy consumption was found using this information. CERF data also had efficiency data of the new lights. With this, the energy efficient direct energy consumption was estimated for the same amount of usage. It was found that the metal halide lights consumed 1,517,747 [MJ/yr] and the LED lights consumed 374,043 [MJ/yr].

Implementation Costs:

The cost to purchase and install the metal halide lighting system and the LED lighting system was known from CERF data. This was used to find the base case and energy efficient cost of implementation. It was found that the cost to install and maintain the metal halide lighting system was 9,504 [$/yr], and the cost to install and maintain the LED lighting system was 8,721 [$/yr].

Device-level Rebound:

The device-level rebound was calculated by analyzing lighting usage numbers from CERF data. The average amount of hours the lights were used with the old metal halide lights was compared to the average amount of hours the new LED lights are used. The percent increase in usage was used as device-level rebound, which was found to be 14.58%.

Price of Energy:

The price of energy used for electricity was obtained from CERF data and is an average of the amount that Calvin pays for electricity. This was determined to be 0.0227 [$/MJ]

Device 2: Cars

Assumptions:

From collaboration with the other groups studying cars, it was determined that the lifetime of each car would be 12 years and the total mileage driven would be 15,000 miles per year. This was determined by finding an overall average life and usage of many cars (Lee), and this was standardized between groups so that easy comparisons could be made.

Embodied Energy:

To calculate the total embodied energy of both the base case, a 2014 Toyota Corolla, and energy efficient case, a 2014 Toyota Prius, a published paper was used that had detailed material weight breakdowns of each car (Onat). These weights were multiplied by their respective embodied energy coefficients (University, Victoria Wellington). The sum of these terms gave the total embodied energy, and this was divided by the lifetime of the car to determine the average embodied energy per year. It was found that the Corolla has an embodied energy value of 2,911 [MJ/yr] and the Prius has an embodied energy value of 4,340 [MJ/yr].

Direct Energy Consumption:

The direct energy consumption of each of these devices is based solely on their gasoline consumption in a year. The fuel efficiency of each car was found based on the average value found on Edmunds.com (Edmunds). This was found to be 32 miles per gallon for the Corolla and 50 miles per gallon for the Prius. Using this information, the total gasoline used in a year could be found using the total amount driven, which was assumed to be 15,000 miles. This was then multiplied by the energy content in gasoline (127 MJ/gal, Victoria) to determine the direct energy consumed in each case. It was found that the Corolla consumes 59,531 [MJ/yr] in gasoline and the Prius consumes 38,100 [MJ/yr] in gasoline.

Cost of Implementation:

The replacement cost for each device in made up mainly by the cost to buy each car. This was found using the cost from Edmunds.com for each car (Edmunds). The cost to buy a 2014 Toyota Corolla is $16,800 and a 2014 Toyota Prius is $24,200. Also included in the replacement cost is the cost to service and maintain each car. This was found in (Anan) and was determined to be $358 per year for the Corolla and $424 per year for the Prius. The purchase cost was divided by the expected lifetime of 12 years and added to these maintenance costs to find total replacement costs per year. It was found that a Corolla costs 1,400 [$/yr] to own and maintain and a Prius costs 2,017 [$/yr] to own and maintain.

Device-level Rebound:

Device-level rebound was found from a study that compiled many different sources for car device-level rebounds (Lee). This study concludes that people do in fact drive more on average when they have a more fuel-efficient car. The amount of increased driving, however, differs depending on the situation. To find a value to use, several studies were compiled and averaged to give a device-level rebound of 6.04%.

Price of Energy:

The price of gasoline was standardized between several groups and was found by finding the average price of fuel in the United States over the last 5 years. This was determined to be $2.69 per gallon (Anon).

Results

With all the variables described above known or calculated, the economy-wide rebound for each system could be found using the Equations in Appendix A1. Total economy-wide rebound was broken into its three components of device-level rebound, embodied energy effects, and re-spending.

Table D.1: Lights - Calculation Parameters

	Base Case	**EE Case**	**% Change**
Lifetime [yr]	4	20	80
E_{emb} [MJ/yr]	6,691	15,184	56
E_{dir} [MJ/yr]	1,519,747	374,043	75
C_{repl} [$/year]	9,504	8,721	-9
Price of Energy [$/MJ]	$0.023		
ε [-]	0.0074		
Υ [-]	-0.030		
Re_{dev} [%]	14.6		
Re_{Ew} [%]	164		

Table D. 2: Lights - Contribution to Energy-Wide Rebound Effect

	Re [%]	**Φ [-]**
Device	14.6	0.089
Embodied	0.7	0.005
Respending	148.2	0.906
Economy Wide	164	1

Table D.3: Cars - Calculation Parameters

	Base Case	EE Case	% Change
Lifetime [yr]	12	12	0
E_{emb} [MJ/yr]	2,911	4,340	33
E_{dir} [MJ/yr]	59,531	38,100	36
C_{repl} [$/year]	1,400	2,017	31
Price of Energy [$/MJ]	$0.021		
ε [-]	0.0667		
ϒ [-]	1.364		
Re_{dev} [%]	6.0		
Re_{Ew} [%]	-54		

Table D. 4: Contribution to Energy-Wide Rebound Effect

	Re [%]	Φ [-]
Device	6.0	-0.113
Embodied	6.7	-0.125
Respending	-66.3	1.237
Economy Wide	-54	1

Analysis

Device 1: Lights

It is estimated that the impact of implementing a project where incandescent bulbs are changed to LED bulbs would backfire and have an economy-wide rebound of 164%. These results may be considered surprising as the consensus of using LED lights is that they save money and that they are better for the environment. There is some device-level rebound, meaning that the new lighting system is used more energy than the old lighting system. This is most likely since the new lights can be turned on immediately and do not need to warm up, which encourages their use. The embodied energy difference between the two systems ended up being negligible. The economy-wide rebound is high, mostly due to the re-spending effect. This is because it is assumed that Calvin is spending the money that they are saving on electricity on the new system, which is re-spent in the economy and driving up energy usage. As these energy savings continue, the large amount of money that is saved by the T&T will continue to be re-spent in the economy, causing the rebound effect.

Device 2: Cars

It is estimated that the impact of driving a hybrid car instead of a gas car will have an economy-wide rebound of -54%. This means that more energy will be saved than expected. The rebound associated with embodied energy and device-level changes were both small positive numbers, meaning that they take away a small amount of the energy savings. This is because the hybrid car requires greater energy input to manufacture due to its battery, and drivers drive more when their car is more fuel efficient. These effects, however, are relatively small compared to the re-spending effect. Since the cost of implementation is greater than the price of energy saved each year, money is taken out of the economy, which results in less money to be re-spent; therefore, the overall energy consumption in the economy decreases. This is a surprising and hopeful result, as implementing this energy efficiency intervention will lead to more energy savings than expected.

Conclusion

The team studied economy-wide rebound effects of replacing metal halide lights with LED lights and replacing a gas car with a hybrid car. It was determined that Calvin's recent change from metal halide lights to LED lights in its T&T building resulted in 164% economy-wide rebound. This means that this energy efficiency intervention backfired and did not save energy in the economy. This is mostly due to the re-spending effect, as the money saved is re-spent in the economy. Next, it was determined that a switch from a 2014 Toyota Corolla to a 2014 Toyota Prius will result in an economy-wide rebound of -54%. This means that even more energy will be saved than expected from just fuel savings. Again, this is mainly due to re-spending. Since the Prius is more expensive, there will be less money in the economy and less energy consumed. It can be concluded that the overall economy-wide rebound of energy efficiency interventions depend on the specific systems being implemented. While some energy efficiency interventions end up having a negative overall energy impact, some end up saving more energy than anticipated.

Appendix D1: Sources

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Appendix D2: Device Pictures

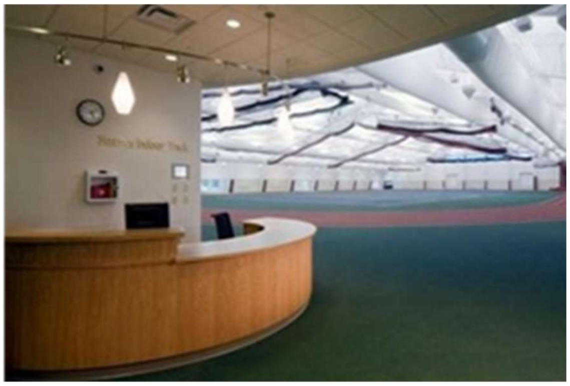

Figure D2. 1: Base Case: Metal Halide Lights in TNT

Figure D2. 2: Energy Efficient Case: LED Lights in TNT

Figure D2. 3: Base Case: 2014 Toyota Corolla

Figure D2. 4: Energy Efficient Case: 2014 Toyota Prius

Appendix E: Windows and HVAC

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Dr. Heun and Dr. Brockway

Engineering 333: Thermal Systems Design

December 18, 2019

Introduction

Over the past several months, the Engineering 333 class at Calvin University has been conducting research with the goal of determining the economy-wide rebound effect which occurs when new energy efficient technologies are adopted. This was done by analyzing individual devices though their embodied energy, direct rebound, and re-spending effect. The students in this class were grouped into teams, with each team researching the rebound effect of two different energy efficient technologies. In this report, the results of the studies done by Team 4 are discussed, who studied the economy-wide rebound effect of dormitory windows and residential furnaces.

Device 1: Dormitory Windows

For the dormitory windows, the base case was the standard dorm window found on Calvin University's campus with a window from the floor Second Bolt being used as the specific case (Figure E. 1). The energy efficient window was a Marvin Glider Window quoted as 78JSZNK from The Window Center.

Figure E. 1: The Standard Dormitory Window at Calvin University

Windows were chosen to be analyzed as they are a relatively cheap option to examine when it comes to energy savings. While the window itself does not use power, it has a profound impact on the heat leakage of a house or in this case dorm room which can affect energy usage rates. As Calvin students, most of the team had experience with a very hot or very cold dorm room. Since the windows are only single-pane, the switch to a double-pane window was desired to be analyzed.

Device 2: HVAC

For the residential furnace study, the base case was chosen to be a furnace in a Grand Rapids, Michigan duplex. The model that is in this duplex is the Lennox G12Q3E-82C-6. The research concluded that the most efficient furnace currently on the market is the Lennox Signature SLP98UH090XV60C furnace that has 98.7% AFUE with an 88,000 BTU input capacity (Lennox). AFUE is the measure of how efficiently the furnace converts its fuel to heat annually. Furnaces were chosen to be studied because furnaces directly use fuel, have opportunity for significant efficiency increases, and are relatively expensive to replace in comparison to windows. Additionally, in the large number of colder climates, furnaces are invaluable. Due to this, a more efficient furnace that is used frequently may have a large impact on rebound.

Figure E. 2: Energy Efficient Furnace (Lennox Signature SLP98UH090XV60C) at left and Base Case Furnace (Lennox G12Q3E-82C-6) at right

Methods

First, the embodied energy of each device was determined (Appendix E1). Next, the direct energy saved of each device was determined (Appendix E2). Then, the cost of replacement was determined for each component using multiple estimates which are described in Appendix C. Finally, the rebound calculations (Appendix E3) were used to determine the economy-wide rebound for the device along with each component of the economy-wide rebound: device-level rebound, embodied energy rebound, and the re-spending rebound.

Results

Table E. 1: Dryers Contribution to Energy-Wide Rebound Effect

	Base Case	EE Case	% Change
Lifetime [yr]	20	20	0
E_{emb} [MJ/yr]	30	49	39
E_{dir} [MJ/yr]	5,254	1,416	73
C_{repl} [$/year]	66	97	32
Price of Energy [$/MJ]	$0.005		
ε [-]	0.0050		
ϒ [-]	1.615		
Re_{dev} [%]	0.0		
Re_{Ew} [%]	-22		

Table E. 2: Contribution to Energy-Wide Rebound Effect for Dorm Windows

	Re [%]	Φ [-]
Device	0.0	0.000
Embodied	0.5	-0.022
Respending	-22.7	1.022
Economy Wide	-22	1

Table E. 3: Residentials Furnaces Calculation Parameters

	Base Case	EE Case	% Change
Lifetime [yr]	10	10	0
E_{emb} [MJ/yr]	219	290	25
E_{dir} [MJ/yr]	109,880	83,113	24
C_{repl} [$/year]	378	398	5
Price of Energy [$/MJ]	$0.011		
ε [-]	0.0027		
ϒ [-]	0.073		
Re_{dev} [%]	20.0		
Re_{Ew} [%]	77		

Table E. 4: Residential Furnaces Contribution to Economy-Wide Rebound Effect

	Re [%]	Φ [-]
Device	20.0	0.261
Embodied	0.3	0.003
Respending	56.5	0.736
Economy Wide	77	1

Analysis

Device 1: Dormitory Windows

For windows, it was somewhat surprising that the economy-wide rebound ended up being negative, meaning that the energy savings of the window for the price are not justified by the cost difference to the consumer; however, it is still good for the environment. Respending made up almost all the rebound as there was no device level rebound, and the embodied energy had minimal change. Thus, the energy savings will not overcome the cost of replacement for the windows, meaning hyperconservation will occur for windows.

Device 2: HVAC

For furnaces, the results were as expected. The economy wide rebound was found to be 76.8%, meaning that replacing an old furnace with a newer more efficient furnace will result in energy savings but less than what is expected across the economy. This is expected as with furnaces device-level rebound occurs as well. Therefore, rebound throughout the economy is expected for the furnace and does indeed occur as a result of both device-level rebound and respending.

Conclusion

The team completed research on both a base case and energy efficient case for windows and furnaces. Values for the economy-wide energy rebound of the windows and furnace were solved by using the embodied energy, direct rebound, and re-spending effect for each unit. The economy-wide energy rebound values seemed reasonable for both cases. The economy-wide energy rebound values give insight on whether it makes sense to go forward with changing the base case windows and furnace to the more energy efficient models. Replacing single-pane dormitory windows for double-pane will not be a good personal economic decision, but more energy will be saved than originally expected. Replacing an older furnace will have rebound; thus, less energy will be saved than expected; however, energy is still saved without having a backfire in the economy.

Appendix E1: Embodied Energy Calculations

Windows

For the embodied energy of the windows, the dimensions of the base case window were measured by hand. After obtaining the dimensions, the volume of the aluminum frame with a hollow interior was calculated along with the volume of the glass and adhesive used between the glass and frame (assumed to be silicon). With the volumes of each component of the window, the mass was found for each component by multiplying by the densities of each material. Finally, using the embodied energy per kilogram material list provided by the executive team (Victoria University Wellington 2003), the embodied energy was found for the base case window. This process was repeated with the new window, adding a quarter inch to the frame size and the extra pane of glass along with the new adhesive.

Furnace

For the base case furnace, material weights were estimated using a case study on furnaces (Shaw 2003). This study was done on furnaces very similar to the base case model and gave a bill of materials for an entire furnace. The weights from this study were used as the material weights of the base furnace, aside from the insulation weight, which was raised slightly from the study in order to be more accurate to the furnace being studied. The embodied energy was found by multiplying the material weights by the associated embodied energy coefficients (Appendix A3) for each material. The sum of this result gave the embodied energy of the device.

For the new energy efficient furnace, a schematic from the manufacturer was used to determine the weights of all the materials that were used to make the new energy efficient furnace (Lennox). The schematic detailed the size of the cabinet which was assumed to be made of sheet-metal that is 20-gauge steel with fiberglass insulation also assumed to be covering the inside of the cabinet at a thickness of 0.125 in. For the heat exchanger, a patent was found with select dimensions and material. From this information, more dimensions were estimated. The heat exchanger was listed to be made of aluminized steel, but because aluminized steel was not in the resources for embodied energy coefficients, it was assumed to be stainless steel. The fan size was given but the motor was assumed to be a combination of copper windings and steel casing. This furnace features a larger circuit board to control the variable fan speed, and this board was modeled to be a sheet of copper. Using all the different sums of the materials then multiplying these weights by their associated embodied energy coefficients (Appendix A3), the total embodied energy for the newer, more efficient furnace was found from those values.

Appendix E2: Direct Energy Calculations

Windows

For finding the "energy" used by the window each year, the heat leakage was calculated across the window. To calculate the heat leakage across the window, the following equation was used:

$$\dot{Q} = A\Delta \mathrm{TR}$$

Where A is the area of the window; ΔT is the temperature difference between the outside temperature and inside temperature, and R is the R-value of the window which is the thermal resistance to heat transfer (Oliva 2005).

This equation only accounts for the heat flux at a specific time; thus, the average outside temperature was found for each month in Grand Rapids (NCEI 2010). The inside temperature of the room was maintained 65°F at night and 72°F during the day. Thus, the average heat flux could be calculated for each month in terms of Watts. To get the energy loss through the window per month then the heat flux was simply multiplied by the time of each month in seconds. However, heat loss had to be accounted for in both the "summer" and "winter." Thus, when the change in temperature was positive, it was considered a cooling cost and vice versa. The absolute value of each energy value was then taken and added together to get the total heat leakage of the room as a result of the window.

For determining the R-values of the windows, windows are usually given a U-value which is the inverse of the R-value in their specifications. The U-value of the energy efficient was given to be 0.29, so the inverse of this was taken and converted to SI units to get the R-value of the energy efficient case. For the base case, the Calvin Physical plant did not have the specifications for the dorm window readily available; thus, a value for the R-value of a standard single pane value was researched and found to be 0.9 °F(hr)(ft^2)/BTU or 0.1638 K(m^2)/W (GreenRiverside).

Furnace

Energy usage for the base case furnace was estimated similarly to the energy efficient case using a study of several Canadian homes. It was decided that due to the similar latitude of this study to the location where the actual base furnace resides, it was decided that this would be accurate to what the base furnace would experience. Since this study was done for a furnace with 95% AFUE, the calculated energy per year was scaled by the AFUE of the base case furnace. This value was the used as the Direct energy of the device as can be seen in Table 3.

Energy usage for the energy efficient furnace was estimated using a study of several Canadian homes. This study provided the fuel used per year by a 95% AFUE furnace in a 230 m^2 house. The fuel used by this furnace was 2211 m^3/year with the home being located in Toronto. Using a conversion from volume to energy per year, the final value was known.

Appendix E3: Cost of Replacement Calculations and Estimates

Windows

For the replacement cost for each case, the cost of installment, cost of replacement, and base cost were determined for both the energy efficient and base case windows along with the maintenance and cleaning costs. However, the cost of replacement/disposal, cleaning cost, and maintenance cost were considered to be the same for each window. Calvin charges students $150 for a broken window (Van Kooten 2019); thus, this value was taken to be the replacement cost for a standard dorm window at Calvin for both material and labor. The physical plant also stated that about 30 minutes per year is spent on maintenance for each window. Thus, the maintenance cost included paying a worker $13 per hour for this window with a $15 material cost for any fix that is necessary, making a total of $21.50 per year in maintenance. For window cleaning, a worker spends around an hour a year on cleaning; thus, the $13 per hour labor cost was used along with a $5 material cost to estimate the cleaning cost to be $18 per year. For the installation cost, the total was estimated by saying two skilled labors valued at $16 would work for two hours along with $20 worth of extra costs. Finally, the base cost of the energy efficient window was given by the quote from the Window Center (Bratt 2019) to be $924.43. For the base case window (the current dorm window) did not have an actual price according to the Physical Plant. Thus, a few estimations were used to determine the base price of the current dorm window. First, an estimation was done by calculating the glass price from a glass price on Home Depot and adding the aluminum frame found on Amazon. This value was confirmed by finding a cheap window of the same style and size from Lowe's. Although the window was double-paned, it was of much lesser quality and could be assumed to be similar to that of a single-pane window. The price from the first estimation was determined to be $384.14. Finally, the costs were all summed and divided by the lifetime cycle of the windows which was determined to be 20 years (Quality Window & Door 2017).

Furnace

The energy efficient furnace is the model that would be replacing the furnace in the duplex. A quote was obtained from a local Lennox furnace dealer. This cost summed with the scrap price of the old furnace enabled the cost of the replacement of the new furnace to be determined.

To determine the cost of replacement, installation was estimated for the base case furnace from furnace installation estimates in Grand Rapids, MI (HomeGuide 2019). This value can be seen as the cost of replacement of the base case in Table 3.

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Appendix F: Windows and Automobiles (Gasoline)

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Engineering 333: Thermal Systems Design

December 18, 2019

Introduction

This report focuses on detailing the findings of energy efficiency interventions in two cases: a change from a double-pane to triple-pane window in Devries Hall (device 1), and a switch from a premium, automatic model with a sportier engine to a basic, manual model with a smaller engine (device 2). The analysis for these two devices will be done to determine if switching to an energy efficient model actually saves energy.

For the Windows device, a 5'x5' double pane (base case) window in Calvin's DeVries hall was selected to model against a 5'x5' triple pane version (EE case) of the same window. For the Gasoline fueled cars device, a 2013 model of the Ford Fusion is used to compare the 2.0L, automatic premium model (base case) to the 1.6L, manual basic model (EE case). The body of the car is exactly the same except for the engine and the transmission.

Methods

Device 1: Windows

Embodied energy values for both window cases were found by using research done at the National Institute of Applied Sciences of Strasbourg[1]. The research conducted provided coefficients relating embodied energy of both glass and wooden framing to surface area of both double and triple pane windows.

To calculate the direct energy usage for both the base and energy efficient windows, Group 5 utilized the "U-factor" of the windows which was provided in the quote for windows from Anderson. The U-factor for a window is an indication of the windows resistance to heat flow, with lower values indicating higher resistance to heat flow, and units of BTU per hour, per square foot, per degree Fahrenheit. The U-Factors were 0.18 $\frac{BTU}{hr*ft^2*°F}$ and 0.27 $\frac{BTU}{hr*ft^2*°F}$ for the energy efficient and base case windows respectively. These factors were converted into metric units of joules per second per square meter per degree Celsius. By using the U-Factor from Anderson and the temperature differential between the window interior and exterior, group five calculated the amount of heat that was transferred through the window and determined the amount of energy needed to either add or remove that heat via a heater or AC unit.

Table F. 1: Assumptions for Window Case. For full Excel calculations, see Appendix F1.

Assumption	Source
Monthly high represents daytime temp for 12 hours. Monthly low represents nighttime temp for 12 hours.	Temperature data from National Oceanic and Atmospheric Administration for the Grand Rapids weather station in Michigan.[2]
72°F room temp during day, 65°F at night.	Based on average maintained building temperature.
AC only run during day, but heat run night and day.	Based on extrapolated consumer choice.
COP for furnace is 1 and for AC unit, 1.5.	Based on comparable units.
Windows last for 15 years.	Qualitywindowanddoorinc.com[6]

Device 2: Cars

Embodied energy values were found for the base and EE models of the Ford Fusion by taking the material make up of each vehicle and multiplying each material by the percent of it in the car. [34] The embodied energies resulted in the same value for both cases, since the Fusion car body is exactly the same. Original retail price and average MPG values were taken from Kelly Blue Book for each model of the Fusion. These values were used with the project-wide value of a vehicle lifespan of 12 years. The assumption of 15,000 miles driven/year was used to calculate gallons of gas used in the vehicle's lifetime. This value was multiplied by the group-wide energy in gas value of 127 MJ/gal to obtain a total gas energy value for each vehicle for the whole lifetime and per year. The average national gas cost over the past 5 years was found to be 2.69 $/gal.

Table F. 2: General values used in car calculations. For full Excel calculations, view Appendix F2.

Assumption	Base Case Value	EE Case Value	Source
Material Make-up of Vehicle	n/a		Appendix B[3,4]
Original Retail Price [$]	$32,200	$23,830	Appendix B[5]
Vehicle Lifespan [yrs]	12		Group consensus
Average MPG [miles/gal]	25	29	Appendix B[5]
Miles Driven in One Year	15,000		Group consensus
National Gas Average [$/gal]	2.69		Appendix B[7]
Energy in Gas [MJ/gal]	127		Appendix B[8]

Results

Table F. 3: Summary of calculations performed in Excel for window base and energy efficient cases.

	Base Case	EE Case	% Change
Lifetime [yr]	15	15	0
E_{emb} [MJ/yr]	88	113	22
E_{dir} [MJ/yr]	1,577	1,017	36
C_{repl} [$/year]	67	99	33
Price of Energy [$/MJ]	$0.005		
ε [-]	0.0446		
ϒ [-]	11.511		
Re_{dev} [%]	0.0		
Re_{Ew} [%]	-384		

Table F. 4: Summary of rebound values for window case.

	Re [%]	Φ [-]
Device	0.0	0.000
Embodied	4.5	-0.012
Respending	-388.4	1.012
Economy Wide	-384	1

Table F. 5: Summary of calculations performed in Excel for car base and energy efficient cases.

	Base Case	EE Case	% Change
Lifetime [yr]	12	12	0
E_{emb} [MJ/yr]	4,223	4,223	0
E_{dir} [MJ/yr]	76,200	65,690	14
C_{repl} [$/year]	2,683	1,986	-35
Price of Energy [$/MJ]	$0.021		
ε [-]	0.0000		
ϒ [-]	-3.143		
Re_{dev} [%]	6.0		
Re_{Ew} [%]	643		

Table F. 6: Summary of rebound values for car case.

	Re [%]	Φ [-]
Device	6.0	0.009
Embodied	0.0	0.000
Respending	636.7	0.991
Economy Wide	643	1

Analysis

Device 1: Windows

For the analysis of double-pane to triple-pane windows, the Embodied Energy Rebound (Re_{emb}) is quite low because there is little difference in the material makeup of the window models. This number is negative because the new alternative window takes more energy to manufacture. The rebound on a device-level (Re_{dev}) is zero because there were no foreseeable behavioral changes that would result from use of the new energy efficient window. The re-spending rebound ($Re_{respend}$) of the window was a large negative, and from this it was determined that the energy efficient case was a bad investment for the consumer since it is expensive and also a bad investment for the economy, since the savings from using less energy are not sufficient enough to overcome the cost to buy the energy efficient window and thus there is less money that is recirculated into the economy. It is, however, good for the environment because you are using less energy overall. This is the same case for the economy-wide rebound (Re_{EW}). It is saving a lot of energy throughout the economy but is still an overall bad intervention for the consumer and economy.

Device 2: Cars

For this analysis of Fusion to Fusion models, the Embodied Energy Rebound (Re_{emb})is zero since the body of the cars are exactly the same. The Economy-wide Rebound (Re_{EW}) is at 859.8% meaning that choosing the fuel-efficient version of this car would end up using significantly more energy than the base case. The simpler, energy efficient model has a lower initial cost and a better fuel efficiency, which saves the owner a significant amount of money, which is good for the economy, but because of the re-spending effect coupled with the energy intensity of the economy causes a large rebound. This large economy-wide rebound explains that purchasing a basic model of the Fusion is good for the consumer, good for the economy, but bad for the environment.

Conclusion

The results for rebound on both cars and windows illustrated surprising findings. In the case of the window energy efficiency intervention, the choice to move to a triple-pane window was determined overall to be a poor investment for both the consumer and economy because the savings from using less energy do not cover the expenses of buying a better window, but good for the environment because less energy. In the case of the gasoline car energy efficiency intervention, the choice to buy a more basic model with a better fuel economy was determined to be a wise economical choice, saving money in both purchasing costs and fuel efficiency, but bad for the environment.

Appendix F1: Raw Excel Data and Calculations – Windows

Figure F1. 1: Base Case Devries Hall APW5050 double pane window. EE case includes same window except with three panes and SmartSun Heatlock enhancement (model number is the same).

Temperatue of Room (Night) (F)	Temperature of Room (Day) (F)	Base Case U Factor (-)	Efficient Case U Factor (-)	Base Case Price ($)	Efficient Case Price ($)	Window Size (ft^2)	COP for Furnace (-)	COP for AC Unit (-)	Cost Energy (heating) ($/MJ)	Cost Energy (Cooling) ($/MJ)		Temperature of Room (Night, Winter) (K)	Temperature of Room (Day, Winter) (K)	Base Case R value (K*m^2/W)	Efficient Case R value (K*m^2/W)	Window Size (m^2)
65	72	1.76	1.1356	$ 998.97	$ 1,482.48	25	1	1.5	$0.00440	$0.0227		291.4833333	295.3722222	0.568181818	0.880591758	2.322557
		(multiply imperial ufactor by .132 for metric)							Average	$0.01355						0.306577

							Base Case		Efficient Case		Base - Heating	Efficient - Heating	Base - Cooling	Efficient - Cooling
Month	High (F)	High (K)	Low (F)	Low (k)	Delta T (day)	Delta T (night)	Qdot Day (w)	Qdot Night (w)	Qdot Day	Qdot Night (w)	MJ used	MJ used	MJ used	MJ used
Jan	30	272.0388889	17	264.8166667	-23.3333333	-26.66666667	-95.3796606	-109.0053264	-61.5415583	-70.33320946	-268.5618729	-173.2834448		
Feb	33	273.7055556	18	265.3722222	-21.6666667	-26.11111111	-88.5668277	-106.7348821	-57.1457327	-68.86793427	-256.6257897	-165.5819584		
Mar	44	279.8166667	26	269.8166667	-15.5555556	-21.66666667	-63.5864404	-88.5668277	-41.0277055	-57.14573269	-199.9293943	-128.9998978		
Apr	57	287.0388889	36	275.3722222	-8.33333333	-16.11111111	-34.0641645	-65.8573847	-21.979128	-42.49298072	-131.2969156	-84.7163508		
May	70	294.2611111	47	281.4833333	-1.11111111	-10	-4.5418886	-40.8769974	-2.93055039	-26.37495355	-59.6804162	-38.50743218		
Jun	79	299.2611111	57	287.0388889	3.888888889	-4.444444444	15.8966101	-18.1675544	10.25692638	-11.72220158	-23.87216648	-15.40297287	13.94662593	8.998743411
Jul	83	301.4833333	61	289.2611111	6.111111111	-2.222222222	24.9803873	-9.0837772	16.11802717	-5.861100789	-11.93608324	-7.701486436	21.91612646	14.1408825
Aug	81	300.3722222	60	288.7055556	5	-2.777777778	20.4384987	-11.3547215	13.18747677	-7.326375986	-14.92010405	-9.626858045	17.93137619	11.56981296
Sep	73	295.9277778	52	284.2611111	0.555555556	-7.222222222	2.2709443	-29.5222759	1.465275197	-19.04857756	-38.79227053	-25.02983092	1.992375132	1.285534773
Oct	60	288.7055556	41	278.15	-6.66666667	-13.33333333	-27.2513316	-54.5026632	-17.5833024	-35.16660473	-107.4247492	-69.31337793		
Nov	47	281.4833333	32	273.15	-13.8888889	-18.33333333	-56.7736075	-74.9411619	-36.6318799	-48.35408151	-173.073207	-111.6715533		
Dec	35	274.8166667	23	268.15	-20.5555556	-23.33333333	-84.0249391	-95.3796606	-54.2151823	-61.54155828	-235.737644	-152.1043571		
										SUM:	-1521.850613	-981.9395206	55.78650371	35.99497364

Key:	Notes:
Heating	Assume high temp is average for the day
AC	

	Base	Efficient	Difference	Cost of weighted avg
Energy Usage Per Year (MJ/year):	1577.637117	1017.9345	-559.7026226	$ 0.0050
Cost of energy used Per Year ($/year):	$ 7.96	$ 5.14	$ (2.82)	
Replacement Cost ($/year)	$ 66.60	$ 98.83	$ 32.23	
Embodied Energy (MJ/year)	405.7971014	467.1126	61.3154961	
Respending Rate ($/yr)	$ 58.64	$ 93.69		

Figure F1. 2: Screenshot of Excel calculations for Window comparison.

Appendix F2: Raw Excel Data and Calculations – Cars

Figure F2. 1: Base Case: 2013 Ford Fusion, automatic transmission with a 2.0L engine.

Figure F2. 2: EE Case: 2013 Ford Fusion, manual transmission, 1.6L engine.

Curb Weight	Material	Steel	Cast Iron	Cast Al	Wrought Al	Stainless Steel	Copper	Magnesium	Lead	Zinc	Nickel	nyodimium	Other Metals	Plastics/textiles	Electronics	Rubber	Oils/paint
	Coeffecient (mj/kg)	21.12	10	26	26.7	49.368	12.9	315	25.21	11	1	1	45.39072727	65	42	80	97
1554.461	[Base] 2013 Fusion Automatic	831.2	50	146.4	28.4	19.1	33.7	2.3	10	0	0	0	0	184.2		76.975	72.
		17554.944	500	3806.4	758.28	942.9288	434.73	724.5	252.1	0	0	0	0	11973	0	6158	6993
1554.461	[EE] 2013 Fusion Manual	831.2	50	146.4	28.4	19.1	33.7	2.3	10	0	0	0	0	184.2		76.975	72.
		17554.944	500	3806.4	758.28	942.9288	434.73	724.5	252.1	0	0	0	0	11973	0	6158	6993

Base Model Car	Original Retail Price [$]		AVG MPG	Miles Driven/Year	Lifespan [yrs]	Gal gas used lifetime [gal]		Gas energy [MJ/lifetime]	Gas energy [MJ/year]
2013 Fusion 2L AWD Automatic	$32,200		25	15000	12	7200		914400	76200
2013 Fusion 1.6L FWD Manual	$23,830		29	15000	12	6207		788276	65690

	Total Embodied			Total/12 yrs		Cost/12 yrs	
2013 Fusion 2L AWD Automatic	50673.1	MJ		4222.8	MJ/yr	$2,683	$/yr
2013 Fusion 1.6L FWD Manual	50673.1	MJ		4222.8	MJ/yr	$1,986	$/yr

Constants	
National Gas Average past 5 years [$/gal]	$2.69
Energy in gas [MJ/gal]	127
Actual Cost [$/MJ]	$0.0211
Short term rebound	0.0604

= values that we use in the equations

Figure F2. 3: Screen shot of Excel calculations for Gasoline Car comparison.

	FINAL VARIABLES		
BASE CASE (FUSION 2.0)	$\dot{E}_{emb}$	4223	MJ/yr
	$\dot{E}_{dir}$	76200	MJ/yr
	$\dot{C}_{rep}$	$2,683.3	$/yr
EE CASE (FUSION 1.6)	$\dot{E}_{emb}$	4223	MJ/yr
	$\dot{E}_{dir}$	65690	MJ/yr
	$\dot{C}_{rep}$	$1,986	$/yr
OVERALL VALUES	P_e	$0.0211	$/MJ
	RE_dev	6.04%	
	I	5.21	MJ/$
	k	19	

		EQUATIONS	
Eqn #			
1	$\dot{E}_{cost,dev,emb}$	0.0	MJ/yr
2	$\dot{E}_{sav,dev,dir,expected}$	10510.3	MJ/yr
3	$\dot{C}_{impl}$	-$697.5	$/yr
5	$\dot{E}_{sav,dev,dir}$	9875.52	MJ/yr
18	ε	0.0000%	
20	γ	-314.5%	
Respend		853.8%	
25	Re_EW	859.8%	

Figure F2. 4: Screenshot of Excel calculations for Gasoline Car comparison.

Appendix F3: Sources

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Appendix G: Smart Power Strips and Lighting Control

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Engineering 333: Thermal Systems Design

December 18, 2019

Introduction

The purpose of this project is to analyze how the improvement of device-level energy efficiency saves energy at the economy-wide level. Team 6 analyzes two energy efficient interventions which are using smart power strips and using energy efficient lighting control. The estimated cost of implementation for these two interventions are $94.00 and $50.20, respectively.

Device 1: Smart Power Strips

The base case power strip was represented by the "APC Personal Surge Protector PER8T" as shown in Figure G1.1. The energy efficient power strip was represented by the "APC Power Saving Personal Surge Protector P8VNTG" as shown in Figure G1.2. The smart power strip chosen was a "master-control". This term is defined in Appendix G2. These power strips were chosen because there was readily available data for the embodied energy for both power strips and both power strips were produced by the same company.

Device 2: Lighting Control

The base case and the energy efficient models are shown in Figure G1.3 and Figure G1.4, respectively. The base case model is a normal manual switch and the energy efficient model uses a motion sensor to turn the lights on and off. The lighting control project was chosen because there was CERF data that was readily available for Calvin University laundry rooms.

Methods

Device 1: Smart Power Strips

The embodied energy for both the base case and energy efficient case was found using the "Product Environmental Profile" of the power strips provided by APC, the manufacturer (Schneider Electric). This document provided the mass of each material used in the production and distribution of the power strips. These were then multiplied by their corresponding embodied energy coefficients (Appendix A3) to find the embodied energy. The direct energy consumption of the power strips was dependent on the devices connected to the power strip. The cost of replacement was found by dividing the cost of the power strip by the guaranteed lifetime of the power strip. There would be no other costs in this cost because it does not require a specialist to install a power strip nor does it require maintenance.

Device 2: Lighting Controls

The embodied energy is calculated by dividing the sum of the product of energy efficient coefficients for embodied energy shown in Appendix A3 and weight composition of each material by lifetime. The lifetime is estimated to be 10 years because Calvin University replaces their lighting control systems every 10 years on average. The direct level consumption is obtained from CERF data. The cost of replacement is the sum of the purchase cost, installation costs and recycling. The device-level rebound is assumed to be zero because installation of the motion-based lighting controls would not cause any behavioral changes for Calvin University students.

Results

Device 1: Smart Power Strips

Table G.1 shows the economy-wide rebound parameters. Table G.2 shows how device-level rebound, embodied energy and re-spending contribute to economy-wide rebound.

Table G.1: Smart Power Strips Calculation Parameters

	Base Case	EE Case	% Change
Lifetime [yr]	5	5	0
E_{emb} [MJ/yr]	4	34	87
E_{dir} [MJ/yr]	1,620	774	52
C_{rep1} [$/year]	1	18	94
Price of Energy [$/MJ]	$0.040		
ε [-]	0.0348		
ϒ [-]	0.509		
Re_{dev} [%]	0.0		
Re_{Ew} [%]	149		

Table G.2: Smart Power Strips Contribution to Energy-Wide Rebound Effect

	Re [%]	Φ [-]
Device	0.0	0.000
Embodied	3.5	0.023
Respending	145.3	0.977
Economy Wide	149	1

Device 2: Lighting Control

Table G.3 shows the economy-wide rebound parameters. Table G.4 shows how device-level rebound, embodied energy and re-spending contribute to economy-wide rebound.

Table G.3 Lighting Control Calculation Parameters

	Base Case	EE Case	% Change
Lifetime [yr]	10	10	0
E_{emb} [MJ/yr]	1	14	95
E_{dir} [MJ/yr]	4,012	1,157	71
C_{rep1} [$/year]	1	5	76
Price of Energy [$/MJ]	$0.023		
ε [-]	0.0047		
ϒ [-]	0.059		
Re_{dev} [%]	0.0		
Re_{Ew} [%]	158		

Table G.4: Lighting Control Contribution to Energy-Wide Rebound Effect

	Re [%]	Φ [-]
Device	0.0	0.000
Embodied	0.5	0.003
Respending	157.8	0.997
Economy Wide	158	1

Analysis

Device 1: Smart Power Strips

The base case power strip had four times the lifetime of the energy efficient power strip because of the complexity of the smart power strip. The embodied energy difference was expected because of the complexity mentioned previously. The direct energy consumption of the base case was more than twice the energy consumption of the energy efficient case. This is because of the previously mentioned model where power is shut off for a longer period of time for the base case. The results show that the base case power strip allows more energy consumption than the smart power strip. Even though the smart power strip has a higher embodied energy the energy consumption difference more than covers for this disadvantage. Because the models were made with an assumption that there was no behavioral change with the smart power strip, there is no device-level rebound. This leaves the economy-wide rebound to be dominated by the re-spending rebound as the effect of the embodied rebound is not as significant as the re-spending rebound.

Device 2: Lighting Controls

The results show that the direct level energy consumption for the bases is about 3.5 times higher than that of the energy efficient model. The embodied energy for the energy efficient model is 14 times higher than the embodied energy for the base case because the energy efficient model has more materials that are used for the controls and it also mostly plastic. The economy-wide rebound is 160% and it is mostly due to the re-spending effect. An economy-wide rebound this high shows that the installation of a motion-based lighting control system for Calvin University has the potential to backfire.

Conclusion

The purpose of this project is to analyze how the improvement of device-level energy efficiency saves energy at the economy-wide level. Team 6 analyzes two energy efficient interventions which are using smart lighting control and using smart power strips. It was found that the economy-wide rebound for smart power strips and the motion-based lighting control systems is 149% and 158% respectively. This shows that both energy efficiency interventions have the potential to backfire. For both energy efficient interventions, re-spending is the driving factor contributing to the economy-wide rebound. This shows that energy efficient interventions are good for the economy but bad for the environment. Future studies should focus more on decoupling economy and environmental impacts.

Appendix G1: Device Pictures

Figure G1. 1: APC Personal Surge Protector PER8T

Figure G1. 2: APC Power Saving Personal Surge Protector P8VNTG

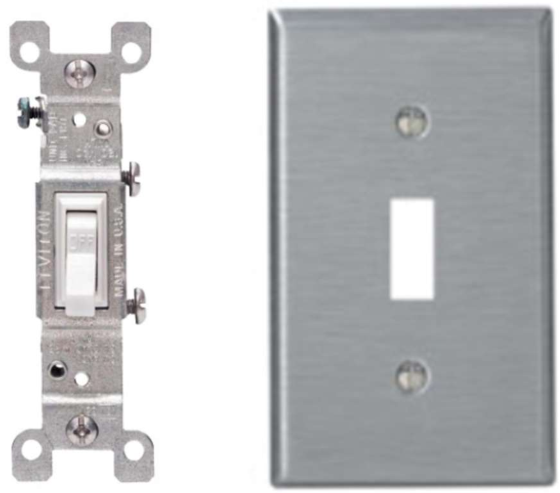

Figure G1. 3: Lighting Control Base Case Model:

Switch: M24-01451-2WM

Cover: 1-Gang 1-Toggle Standard Size Stainless Steel Wall Plate, Stainless Steel

Figure G1. 4: Lighting Control Energy Efficient Case Model Parts:

Switch: MS-OPS5MH-WH

Cover: 1-Gang Decora Wall Plate, Stainless Steel

Appendix G2: Smart Power Strips Data and Assumptions

"Master control" means that an outlet is chosen as the "master" where when the device is turned on, the power strip will supply power to the remaining outlets. But when the "master" device is turned off, the remaining power strips will not be connected and therefore save energy.

The model explained in Table G2.1 was used to determine the direct energy consumption. The usage level for each device is categorized into Active, Absent, and Off. It is expected that the power strip will not allow the TV to be on standby mode because the TV will be the "master" control. When the "TV" draws power under a threshold, the smart power strip will assume that the "master" turned off and so would cut power to the other devices. Each usage level has its unique device power draw (Wang and Zhang, 2014). This is explained in Table G2.2.

Table G2. 1: Model for Energy Use

	Base Case			Energy Efficient (Tier 1)		
	Active	Absent	Off	Active	standby	Off
Device	expect (hr/day)	expect (hr/day)	expect (hr/day)	expect (hr/day)	expect (hr/day)	expect (hr/day)
TV	2.95	1.94	19.11	4.89	0	19.11
XBOX	1.4	7.46	15.1	1.4	3.49	19.11
DVD	0.778	23.2	0	0.778	4.112	19.11
Audio	2.95	1.94	19.11	4.89	0	19.11

Table G2. 2: Power Draw for each Device and Status

Base Case	Device Wattage (W)			
Device	active	absent	off	standby
TV	90	90	0.2	0.2
XBOX	100	93	0.2	0.2
DVD	5.3	5.3	0.2	1
Audio	0	0	0.2	0.2
Efficient	Device Wattage (W)			
Device	active	absent	off	standby
TV	90	90	0	0.2
XBOX	100	93	0	0.2
DVD	5.3	5.3	0	1
Audio	0	0	0	0.2

The equations to find the direct energy consumption is given in Equations G2.1, G2.2, G2.3. They explain the energy used by a device every day is found by multiplying the duration of use and the power draw of the device at the usage level. The direct energy consumption of the base case is the sum of the energy used by the devices every day for the year. The direct energy consumption of the energy efficient case is the sum of the energy used by the devices every day for the year multiplied the factor of 100.02% to account for the energy required to monitor the power draw from the smart power strip itself.

$$E_{dev,use,daily} = t_{dev,use,daily} P_{dev,use}$$ Equation G.2. 1

$$\dot{E}_{dir,base} = \left(\sum E_{dev,use,daily}\right) 365 \left[\frac{days}{year}\right]$$ Equation G.2. 2

$$\dot{E}_{dir,EE} = \left(\sum E_{dev,use,daily}\right)(100.02\%) 365 \left[\frac{days}{year}\right]$$ Equation G.2. 3

Appendix G3: Lighting Control Data and Assumptions

In order to calculate the direct energy consumption of the base case and energy efficient case, the following assumptions were made:

- The CERF data is accurate
- The light bulbs remain the same
- The number of lights per laundry room remains the same
- After installation of the energy efficient case, there are no behavioral changes. That is device-level rebound is 0.

Appendix G4: Sources

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Appendix H: LED Lighting and Residence Hall Windows

Team A: Josh Hallenbeck, Cameron Ilbrink, Bridget Pertzsch, Lillie Spackman

Dr. Heun and Dr. Brockway

Engineering 333: Thermal Systems Design

December 18, 2019

Introduction

Over the past several months, the Engineering 333 class at Calvin University has been conducting research with the goal of determining the economy-wide rebound effect of adopting new energy efficient technologies. The students in this class were grouped into teams, with each team researching the rebound effect of two different energy efficient technologies. In this report, the results of the studies done by Team A on the economy-wide rebound effect of LED lightbulbs and residence hall windows are discussed.

Light bulbs are a common energy-consuming device in nearly every living space. Their widespread use and relatively low cost make them a good candidate for an energy efficiency study. This study investigated the energy-related impact of replacing a halogen light bulb with an LED light bulb.

The marketing of some products emphasizes the energy efficiency; these claims of energy efficiency are worth examining. One such category of products that promotes energy efficiency is windows. In the setting of a university campus, many of the windows are in residence halls; thus, the decision was made to examine residence hall windows (See Figure 1). Although there are similarities between the residence hall windows between halls, the windows are not identical. After examining windows in multiple residence halls and contacting the campus physical plant, it became clear that the precise window models in the residence hall could not be identified.

Figure H. 1: Dorm room window in Schultze-Eldersveld Hall at Calvin University

Methods

At the outset of the project, both devices of interest were identified. Subsequently, base case situations were identified, as were the singular energy efficiency case of interest. Using these two products (base case and energy efficient), further analysis was performed.

Device 1: LED Lightbulbs

Light bulbs were selected from an online catalog from Home Depot. A 790-lumen halogen light bulb was first selected (Home Depot, 75), and an LED light bulb was chosen at a similar luminosity of 815 lumens (Home Depot, 60). Parameters for calculations were obtained from the manufacturer's listed specifications, including cost per unit, expected lifetime (in years, based on a usage rate of 3 hours/day), and rate of energy consumption. These data were used to calculate the rebound parameters of device lifetime, direct energy consumption rate, and cost of replacement rate. The cost of energy was obtained from CERF data and was calculated as an average of the amount that Calvin University pays for electricity. The embodied energy of a halogen light bulb was found using embodied energy coefficients (University). A bulb was sealed inside a bag and the weight of both were recorded. The bulb was then shattered inside of the bag, metal components were removed, and the bulb was weighed again. The metal components accounted for less than two percent of the total weight. The embodied energy was calculated using the embodied energy coefficient for float glass, with the total bulb weight attributed to glass. The embodied energy of the LED light bulb was found using an estimate of 1/66 of the total direct energy consumption (Tsao). A value for the device-level rebound of LED light bulbs was found in an article which calculated the rebound effect of switching to LED bulbs. Tables 1 and 2 show collected and calculated data.

Figure H. 2: Advertised specifications with picture of the halogen bulb

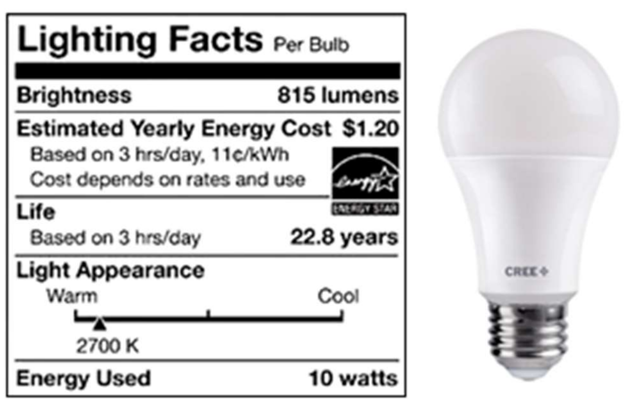

Figure H. 3: Advertised specifications with picture of the LED bulb

Device 2: Residence Hall Windows

Initially, attempts to identify the windows in the residence halls were made. After the window models could not be identified in Bolt-Heyns-Timmer Hall, Beets-Veenstra Hall, or Schultze-Eldersveld Hall, both the campus physical plant and a professor involved with residence hall heating research were contacted and inquiries were placed regarding residence hall window models. Both attempts were unfruitful. Ultimately, a generic window was theorized using values pertaining to window properties and scaled to the appropriate size. The windows in the residence halls are single-pane windows, which was compared to an energy efficient case of triple-pane windows.

Since the specific brand of window was not found, the exact embodied energy for the specific window could not be found. Instead, the components of the window were all divided into their respective masses. The embodied energy per unit of mass for each component was found through research (Hoellinger). This allowed the team to find the total embodied energy of the window by simply adding the embodied energy of each component. Both the base case and the energy efficient windows used sheets of glass held in place by an aluminum frame.

After the windows of interest were identified, the yearly energy usage for each of the two cases (base and energy efficient) was calculated using monthly average high and low temperatures in Grand Rapids, Michigan (NCEI 2010). These average temperatures were used to calculate the heat loss to the surroundings through the window glass, taking into account the area of the window and the physical properties of the window. One such physical property is the R-value, which indicates the thermal resistance of a material (Oliva 2005). The R-value is 0.1638 Kelvin-meters squared per Watt for the base case window (GreenRiverside). The R-value for a double pane window was then scaled up for the energy efficient case, because triple-pane windows are approximately 25% more efficient than double-pane windows (American Vision Windows). The R-values were used to calculate the heat loss through the window, and the resulting costs to keep the dorm room at a predetermined specified temperature.

Results

Table H. 1: LED Lightbulbs

	Base Case	**EE Case**	**% Change**
Lifetime [yr]	1.8	22.8	92
E_{emb} [MJ/yr]	3	1	-343
E_{dir} [MJ/yr]	224	39	82
C_{rep1} [$/year]	1	0	-545
Price of Energy [$/MJ]	$0.023		
ε [-]	-0.0111		
ϒ [-]	-0.224		
Re_{dev} [%]	10.0		
Re_{Ew} [%]	197		

Table H. 2: LED Lightbulbs Contribution to Energy-Wide Rebound Effect

	Re [%]	**Φ [-]**
Device	10.0	0.051
Embodied	-1.1	-0.006
Respending	188.5	0.955
Economy Wide	197	1

Table H. 3: Residence Hall Windows

	Base Case	EE Case	% Change
Lifetime [yr]	20	20	0
E_{emb} [MJ/yr]	30	87	65
E_{dir} [MJ/yr]	5,254	1,133	78
C_{repl} [$/year]	40	99	60
Price of Energy [$/MJ]	$0.005		
ε [-]	0.0137		
ϒ [-]	2.859		
Re_{dev} [%]	0.0		
Re_{Ew} [%]	-67		

Table H. 4: Residence Hall Windows Contribution to Energy-Wide Rebound Effect

	Re [%]	Φ [-]
Device	0.0	0.000
Embodied	1.4	-0.020
Respending	-68.7	1.020
Economy Wide	-67	1

Device 1: Light bulbs

The light bulb replacement had a device-level rebound of 10%, which accounted for 5.07% of the total rebound effect. This is likely due to the relatively low impact of light bulbs on total household energy use. The values for every rebound parameter except embodied energy rebound are positive, which is expected based on the cost and energy saved.

Device 2: Residence hall windows

The residence hall windows had a device-level rebound of 0%. This is because there are no behavioral changes with a more insulated window. It was initially hypothesized that the more efficient windows might result in buildings kept at a higher average temperature during the cooler months or a lower average temperature during the warmer months. However, there was no research found to support this hypothesis. Instead, behavioral changes were minimal. The economy-wide rebound was found to be -67.3%. This signifies that the change to the energy efficient style of windows resulted in less energy being used when looking at the larger picture.

Analysis

Device 1: Light bulbs

Based on the rebound calculations, switching halogen light bulbs for LED light bulbs may not be the most energy-conscientious decision. The economy-wide rebound is 197%, meaning that there is an economy-wide backfire in energy consumption of 97%. The low cost of light bulbs may make this high rebound relatively unimportant, since the change in cost rate is only $0.94/year and re-spending accounts for the highest contribution to the economy-wide rebound at 95.49%.

Device 2: Residence hall windows

While the embodied energy of the residence hall windows did increase with the change to the more efficient, triple-pane style, the direct energy consumption decreased at a higher rate. This shows that in terms of an energy usage standpoint, the triple pane window style is superior. This energy savings is reflected in the cost. The cost of replacement for the energy efficient case is more than double that of the base case, which could limit the viability of the option for certain consumers. The daily energy savings from the triple pane windows are clear; however, they are countered by higher embodied energy and a higher cost of replacement.

Conclusion

Device 1: Light bulbs

LED light bulbs save money and energy at the device-level at the expense of an economy-wide backfire in energy use. The rebound is largely driven by re-spending effects, although the impact of re-spending must be low, since the rate of cost saved by switching to LED bulbs is less than $1.00/year.

Device 2: Residence hall windows

The residence hall windows displayed a clear energy savings with no device-level rebound. While there is no device-level rebound, the re-spending is still an issue. All energy savings from the energy efficient windows still maintain a negative aspect because the saved money is spent on other uses that require energy.

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Appendix I: Motion Sensor Lights and Refrigerators

Team B: Zuber Abdella, Michael Merz, Nathan Schuten, Abigail Willson

Dr. Heun and Dr. Brockway

Engineering 333: Thermal Systems Design

December 18, 2019

Introduction

Over the past several months, the Engineering 333 class at Calvin University has been conducting research with the goal of determining the economy-wide rebound effect of adopting new energy efficient technologies. The students in this class were grouped into teams, and each team researched the rebound effect of two different energy efficient technologies. In this report, the results of the studies completed by Team B on the economy-wide rebound effect of motion sensor light switches and refrigerators are discussed.

The first case that Team B studied was a case where a flip switch was replaced with a motion sensing light switch. The specific case that the team chose to study was replacing the light switch in the first-floor bathroom of the Calvin University Science Building with a motion sensor. This specific room and situation were chosen because there was already data taken by the Calvin Energy Recovery Fund (CERF) team. The data was provided to us by one of the CERF members, Adam Marquart, in an email correspondence on September 11, 2019.

CERF is an on-campus research group dedicated to reducing Calvin University's carbon emissions and generally improving the efficiency and sustainability of the campus. In the summer of 2011, CERF proposed a project to replace all the Science Building bathroom light switches with motion sensors. For the proposal, CERF collected data to calculate potential project cost savings and energy savings. They also conducted a one-year audit after the project was installed.

Team B was able to use some of the data collected by CERF to calculate the numbers necessary to find the economy-wide rebound for one light switch in a simplified room.

The second case that Team B studied was a comparison between purchasing a "normal" (base case) refrigerator and a comparatively energy efficient refrigerator. The refrigerators chosen were the same size and layout and were built by the same manufacturer. This ensured that the energy efficient case was truly a replacement for the base case and was suitable for the same kitchen. The energy efficient refrigerator was chosen because it earned an ENERGY STAR rating. The two cases were researched and analyzed, and the energy rebound effect was calculated.

Methods

Device 1: Motion Sensor Light Switches

The base case light switch and the energy efficient motion sensor used in this study were:

- Industrial Extra Heavy-Duty Specification Grade Switch, Gray PS20AC3GRY (Reynolds, 2019)
- U100-W Wat WHT Ultrasonic PIR Wall Sensor SW 120v 800W w/time delays (Legrand, 2016)

Since a change in switch would also require a change in the cover plate, the following models were chosen for the cover plates in this study:

- 1 Toggle 1 Blank Cover Plates - Spec Grade Stainless Steel SPSB-H (Kyle, 2019 [2])
- 1 Rocker 1 Blank Light Switch Plates - Spec Grade Stainless Steel SPJB-H (Kyle, 2019 [1])

Images of the parts are found in Appendix I2.

The embodied energy for the base case and the energy efficient case were found by using the embodied energy coefficients standardized across groups, the weight percent of each material, and the product lifetime. The composition of the base case light switch came from the part catalog (Reynolds, 2019) and the volume percent of each material was estimated from a CAD drawing of a similar and simplified light switch (Bernie, 2012). The volume percentages were multiplied by the densities of the materials to get the weight percentages. Only materials with a relatively large volume percent were used to calculate the direct energy because the direct energy of the light switch is a small compared to the other forms of energy, so any small amount of material can be considered negligible. The lifetime of the base case light switch was estimated to be 30 years (Mallery, 2013).

In order to calculate the embodied energy for the energy efficient case, a slightly different method was implemented. For the energy efficient case, materials and weight percentages were found in the Product Environmental Profile (PEP) from the manufacturer's website (Legrand, 2016). The lifetime of the switch was also found on the PEP to be 10 years. For calculating the embodied energy of the switch covers, the covers were modeled as simple stainless-steel boxes with open tops and the dimensions that came from the part websites (Kyle, 2019).

In order to calculate the direct energy for the base case and energy efficient case, a simplified room based on the science building bathroom was modeled to get the relative difference in changing *only* the light switch. The data from CERF is from a project which changed the light switches to motion sensors and switching the current light bulbs with more energy efficient light bulbs. CERF did conduct a time study to find the average ‘on’ hours per week for both before and after installation of the motion sensors. The assumptions made for the simplified model are:

- The light bulbs do not change - 32 Watt, T8 bulbs (1000Bulbs, 2019)
- The room contains seven identical light bulbs powered by one switch
- Total hours ‘on’ per week is the same as the numbers reported in CERF data

The direct energy is the amount of Megajoules per year that the lighting in the room consumes if one light switch activates seven light bulbs that are on for some number of hours per year.

According to a survey on the rebound effect as it relates to energy efficiency and consumption, if the introduction of a new device does not promote a behavioral change in the user of the device, then the device-level rebound can be estimated to be between 0-1% (Greening, 2000). For this case, the ‘user of the device’ is an average Calvin University student and the device is in a public restroom. Changing the light switch in the public restroom does not change the behavior of the average student. Therefore, we estimated the device-level rebound for this case to be 0%.

The equation used for the cost of replacement for both the base case and the energy efficient case is:

$$CR = \frac{Purchasing\ Cost + Maintenanc\ \ Cost + Scrap\ Cost + Installati}{Lifetime} \quad \text{(Equation I. 1)}$$

The purchasing costs were obtained from the manufacturers’ websites (Fruit Ridge, 2019) and the CERF data. The maintenance for the base case light switch was estimated to be \$0. The maintenance cost for the motion sensor switch was also estimated to be \$0 from the PEP file.

The scrap cost for the energy efficient case was initially calculated using the weight percent of materials found in the switch and online values for scrap costs (iScrap, 2019), but the number was determined small enough to be negligible. Research on the scrap value of a common light switch also reaffirmed an estimate of a \$0 scrap value (Kitsap, 2019).

The installation cost was estimated by multiplying the cost of labor for installing a light-switch by the time it takes to install a switch. The cost of labor and installation time for the energy efficient case were taken from the CERF data and the installation time for a common light switch was estimated to be 15 minutes.

Device 2: Refrigerators

The refrigerator models used in this study were Frigidaire model FFTR1814TS for the base case and Frigidaire model FFHT1821TS for the energy efficient case. First the embodied energy of each refrigerator was calculated by using the total weight of the refrigerators, found from the Home Depot website (Robson, 2019), (Casey, 2019). The average composition of refrigerators was found and was used to estimate the composition of both refrigerators, since data specific to the refrigerators was unavailable (Eco3e, 2016). The composition and weight of the refrigerators were also found from the Home Depot website, and the class wide source of the embodied energy of materials was used to calculate the total embodied energy of the refrigerators. The generic calculation is shown in Equation 2.

$$E_{emb,total} = \sum Percent_i \times E_{emb,i} \times M_{total} \qquad \text{(Equation I. 2)}$$

Where $E_{emb,i}$ is the embodied energy, i is the material, Percent is the percent of mass that is due to the given material, and M_{total} is the total mass of the refrigerator.

The direct energy consumption for both refrigerators was found from the manufacturing company's website. The cost of emplacement for both cases was calculated by adding the purchase cost of the refrigerator and the recycling costs, and then dividing the sum by the estimated lifetime of the refrigerators. Installation costs were assumed to be zero because Home Depot will do the installation at no additional cost,(iScrap, 2019**)** and the lifetime for both cases was found from other research. **(**Williams, 2019.**)** The cost of replacement for both base and EE cases was calculated using Equation 1. The device-level rebound was estimated to be zero because owning a more efficient refrigerator does not promote behavioral change (Greening, 2000). The economy-wide rebound was calculated using the equation listed in Appendix A1.

Results

Table 1 shows the summary information the motion sensor energy efficiency project.

Table I. 1: Motion Sensor Lights Data and Rebound

	Base Case	EE Case	% Change
Lifetime [yr]	30	10	-200
E_{emb} [MJ/yr]	0	14	97
E_{dir} [MJ/yr]	4,462	1,579	65
C_{repl} [$/year]	1	9	92
Price of Energy [$/MJ]	$0.023		
ε [-]	0.0047		
ϒ [-]	0.121		
Re_{dev} [%]	0.0		
Re_{Ew} [%]	148		

The embodied energy for the energy efficient case is significantly higher than the base case because of the electrical components. The embodied energy coefficient (MJ/kg of a material) for a printed circuit board and other electrical components is 100x larger than the coefficients for the rest of the materials in the motion sensor and the analog switch (Ashby, 2009); this means that per pound, the embodied energy of the circuit board is far greater than the other materials, and contributes to the embodied energy of the EE case being far larger than the base case.

The embodied energy and cost of replacement for the base case are small because they are spread across a 30-year lifespan whereas the energy efficient case is spread across a 10-year lifespan.

Table 2 below shows the percentage that each area of rebound contributed to the overall economy-wide rebound. The re-spending component clearly contributes the most to economy-wide rebound.

Table I. 2: Motion Sensor Lights Rebound breakdown

	Re [%]	**Φ [-]**
Device	0.0	0.000
Embodied	0.5	0.003
Respending	147.4	0.997
Economy Wide	148	1

As shown in Table 3, the embodied energies for the base case and energy efficient case for the refrigerators are identical because the two models that were chosen for this study have the same volume in cubic feet, the embodied energy was calculated using the material weight percentages, and the same weight percent of materials was applied to both refrigerators. The economy-wide rebound is negative since the initial purchasing cost of the EE case is never recouped by the energy savings of the EE refrigerator.

Table I. 3: Refrigerators Data and Rebound

	Base Case	**EE Case**	**% Change**
Lifetime [yr]	14	14	0
E_{emb} [MJ/yr]	437	437	0
E_{dir} [MJ/yr]	1,454	1,307	10
C_{repl} [$/year]	47	53	12
Price of Energy [$/MJ]	$0.040		
ε [-]	0.0000		
ϒ [-]	1.092		
Re_{dev} [%]	0.0		
Re_{Ew} [%]	-27		

The contribution of the different types of rebound are shown in Table 4. All of the economy-wide rebound comes from the re-spending effect for refrigerators.

Table I. 4: Refrigerators Rebound breakdown

	Re [%]	**Φ [-]**
Device	0.0	0.000
Embodied	0.0	0.000
Respending	-27.3	1.000
Economy Wide	-27	1

Analysis

Device 1: Motion Sensor Light Switches

For the motion sensor lights, the embodied energy was found to be much higher in the energy efficient case compared to the base case because the energy efficient case requires a printed circuit board and a sensor. This added complexity and new materials to the EE case which the base case did not require. The difference in direct energy consumption between the two cases was found to be a more significant factor than the embodied energy, so that overall, the energy efficient device saved energy.

The rebound due to the re-spending effect was not 100% in this case because there was also a rebound effect due to the differences in embodied energy of the base case versus the energy efficient case.

Device 2: Refrigerators

For the refrigerators, the embodied energies of both the energy efficient case and the base case were found to be the same. The EE case was chosen to be a similar size and design to the base case. Because it had the exact same weight and both refrigerators were assumed to have the same composition, the embodied energy was the same. Thus, 0% of the rebound effect was due to embodied energy.

Since the difference in embodied energy is zero and device-level rebound is zero, the re-spending effect accounts for 100% of the rebound of the refrigerator. The calculation shows a negative economy-wide rebound. This makes sense since the money saved on electricity each month is not enough to offset the extra purchasing cost up front. Therefore, the customer will never fully recoup the cost of the energy efficient refrigerator, and thus will have less money overall. This means they will spend less money, reducing the amount of energy use caused by re-spending. It should be noted that his is for one comparison of refrigerators, and the price of the refrigerators purchased from the Home Depot fluctuates up and down regularly, which means the negative economy-wide rebound may be subject to fluctuation.

In order to have a positive energy rebound, either the refrigerator would have to be even more efficient, and thus save more money, or the average lifetime of refrigerators would have to be longer, or the cost of energy would have to go up enough that the user was saving money. Once the money spent on the refrigerator is less than the money saved in electricity costs, the rebound becomes positive again.

Conclusion

For both refrigerators and motion sensors, the re-spending effect dominates the energy rebound; it is a much greater effect than device-level rebound. The greater embodied energy is associated with energy efficiency improvements. This is because the energy used by the devices is much greater than the embodied energy of the devices, and the device-level rebound is low due to the purpose of the devices. Both devices are not affected by behavioral changes, since motion sensors are removing behavioral effects, and refrigerators do not have an opportunity to affect behavioral changes.

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Appendix I2: Images of Analyzed Devices

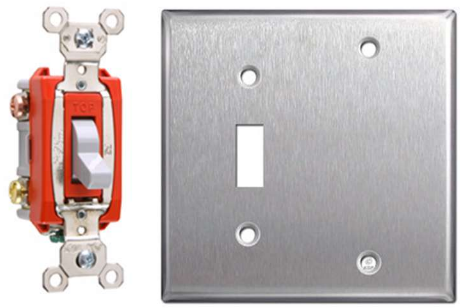

Figure I2. 1: Base case light configuration images

Figure I2. 2: Energy efficient case light configuration images

Figure I2. 3: Base case refrigerator image

Figure I2. 4: Energy efficient case refrigerator image

Appendix J: Hybrid Vehicles and Smart Power Strips

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Dr. Heun and Dr. Brockway

Engineering 333: Thermal Systems Design

December 18, 2019

Introduction

Over the past several months, the Engineering 333 class at Calvin University has been conducting research with the goal of determining the economy-wide rebound effect of adopting new energy efficient technologies. The students in this class were divided into teams, with each team researching the rebound effect of two different energy efficient technologies. In this report, the results of the studies done by Team C on the economy-wide rebound effect of advanced power strips and hybrid automobiles are discussed.

Device 1: Advanced Power Strips

Figure J. 1: Standard (left) and advanced power strips (*TS1810*, n.d.; *Utilitech*, n.d.)

Advanced power strips (APS) are used to reduce standby power usage of audiovisual devices and home office devices. This type of device was chosen because there are opportunities to implement it in different engineering classrooms at Calvin University. The APS model selected for analysis was the TrickleStar® TS1810 (*TS1810*, n.d.). This model was chosen because it is widely available to consumers and because this model was cited in numerous studies that provided values for rebound and direct energy consumption. APS models are typically classified as either Tier 1 or Tier 2 (Hardwick 2018). Our model was a Tier 2 APS, meaning that rather than detecting changes in power usage, the APS monitors user engagement to determine when to disable the power to connected devices. Our model monitors user engagement using an infrared (IR) sensor to detect AV remote activity, and an occupancy sensor (OS) to detect movement of the user. This enables the device to not only reduce standby power usage, but also reduce inactive usage, e.g. when a user has left the television on after leaving the house. For purposes of comparison, a Utilitech basic power strip was selected as the base case, which has no energy saving features (*Utilitech* n.d.).

Device 2: Hybrid Cars

The second device picked for analysis was the standard hybrid car. This device was of interest because is a commonly known example of an energy saving device. Analyzing this energy efficiency intervention would provide an interesting insight into how effective this solution is in the real world. The hybrid model selected for this study was the 2019 Ford Fusion hybrid. This model was picked because there is a non-hybrid version of the same vehicle, the Fusion SE. However, the hybrid model is not a plug-in hybrid, meaning that both devices use the same fuel source (Gasoline). Other than the drive trains, these two cars have the same components which made them directly comparable. It also allowed the use of similar sources to estimate values such as embodied energy.

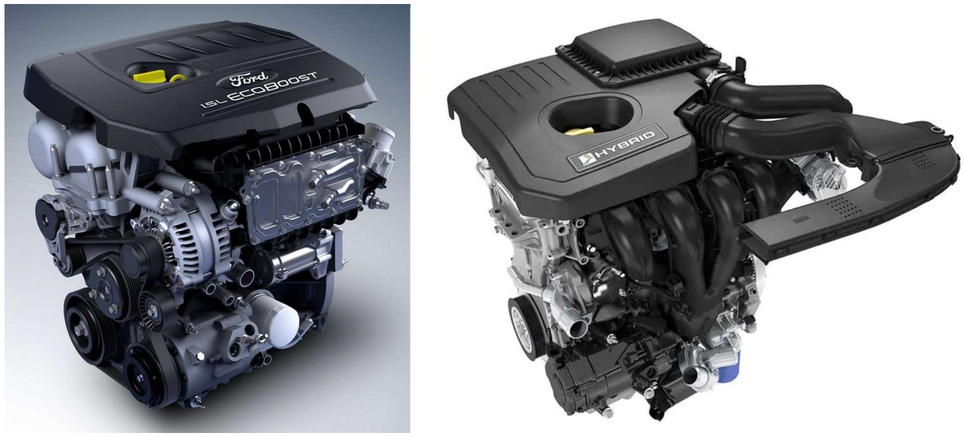

Figure J. 2: 2019 Ford Fusion SE (left) and Hybrid engines (Ford, n.d.)

Methods

To analyze these energy efficient devices effect on economy-wide rebound the following parameters needed to be found. These values were the direct energy consumption, device-level rebound, the replacement costs, and the embodied energy of the devices.

Device 1: Advanced power strips

In our analysis, the direct energy consumption of each power strip was taken to be that of the devices connected to it, as the energy consumption of the power strip itself is negligible. A key parameter for determining the efficiency of a device is its direct energy consumption. For the advanced power strips, the base and energy efficient case consumption were found in a PG&E report that analyzed the power consumption of both standard power strips and Tier 2 APS's in 56 homes (Valmiki & Corradini 2016). The power strips were connected to each household's audiovisual devices. Typical devices included: television, stereo, speakers, DVD player, gaming consoles, and streaming devices. The APS direct energy consumption was not explicitly listed in the report, so it was computed by subtracting the measured savings from the base case energy consumption.

Device-level rebound was calculated using Equation 1 from the direct energy consumption of the base and energy efficient cases, as well as the simulated savings, which were also found in the PG&E report (Valmiki & Corradini 2016).

$$Re_{dev} = 1 - \frac{\dot{E}_{save,dev,dir}}{\dot{E}_{save,dir,expected}} \qquad \text{(Equation J. 1)}$$

Simulated savings were found by installing IR and occupancy sensors in 52 of the sites, as well as plug load loggers. The IR and OS signals were then used to compute the time the plugs would have been disabled by the APS, given the default timer setting of 75 minutes. If no IR signals or motion were detected for 75 minutes, the power would be disconnected.

Replacement costs for each device were found on lowes.com (*Utilitech* n.d.) and tricklestar.com (*TS1810*, n.d.). These costs were then divided by the expected life of the device. The expected lifetime of the APS was estimated as 10 years, based on the TrickleStar's warranty. The basic power strip's lifetime was assumed to be 15 years due to its greater simplicity and because no estimated useful lifetime (EUL) was found in the literature.

Embodied energy was calculated using the product environmental profile for a similar APS that provided a breakdown by weight of the device's material composition (*Product Environmental* 2011). This breakdown was then adjusted to remove packaging materials. The electronic circuit portion of the material (assumed to be PCB) was then removed to find the relative composition of the basic power strip. These compositions were then weighted by the mass of each device and multiplied by embodied energy coefficients from the literature (Victoria University n.d.; Alstone, Mills & Jacobsen 2011).

Device 2: Hybrid cars

To determine the direct energy consumption of the automobiles selected, the fuel economies of both vehicles were found (Lee & Wagner, 2012). Once these fuel economies were known, the assumed lifetime mileage was used along with an assumption that the vehicles were only driving highway miles to calculate the fuel use over the course of the vehicles' life. The volume of fuel was then converted to energy with a standardized value found by the executive team to get the direct energy use over the life of the vehicle.

Equation 1 was used to determine the device-level rebound of switching from the gas-powered Fusion to the Hybrid model.

$$1-\frac{1}{\beta}\beta(1-(1-\beta)\alpha+1) \qquad \text{(Equation J. 2)}$$

In Equation 1, β is the percent initial energy saved by the hybrid vehicle and α is the elasticity of energy service demand with respect to energy cost per energy service. This formula was obtained from a Swedish study on the rebound effects of different devices for a household (Nässén, 2009). For the purposes of this study, the base α value was used and β was found based on the fuel saved by switching to the hybrid car.

The replacement costs associated with the automobiles were calculated using standardized costs of ownership provided by Edmunds.com. The assumptions made included a financing interest rate at 5% and constant depreciation. The resulting replacement costs are shown in Table J3.

To calculate the embodied energy for both the standard and hybrid models of the Fusion, multiple sources were utilized to determine the coefficients of all materials used in the production chain (Dai, et al., 2016; Hawkins, et al., 2012). Using the known mass of the base case vehicle, the mass percent composition and the embodied energy of each material present allowed the embodied energy of the entire base case model to be calculated. The embodied energy of the Fusion Hybrid was calculated using the known mass of the added battery (CEC, 2015) and estimated electric motor mass. This motor mass was found by subtracting the battery weight from the difference in curb weight (Ford, n.d.) between the two models. The motor mass was broken down into its base materials (Hawkins, et al., 2012). Once the vehicle material compositions were determined, the mass of each material was multiplied by its embodied energy coefficient. The embodied energy coefficient for the lithium ion battery was found in the journal *Procedia CIRP* (Thomitzek, et al., 2019).

Results

The values calculated using the methods above were then used to compute the economy-wide rebound using the equations in Appendix A1. The results of these calculations can be seen in Tables J1–J4.

Table J. 1: Calculated Results for Advanced Power Strips

	Base Case	**EE Case**	**% Change**
Lifetime [yr]	12	12	0
E_{emb} [MJ/yr]	6,765	6,959	3
E_{dir} [MJ/yr]	70,556	45,357	36
C_{rep1} [$/year]	6,355	6,714	5
Price of Energy [$/MJ]	$0.021		
ε [-]	0.0077		
ϒ [-]	0.675		
Re_{dev} [%]	20.0		
Re_{Ew} [%]	40		

Table J. 2: Contributions to Economy-Wide Rebound for Advanced Power Strips

	Re [%]	**Φ [-]**
Device	20.0	0.497
Embodied	0.8	0.019
Respending	19.5	0.484
Economy Wide	40	1

Table J. 3: Calculated Results for Hybrid Automobiles

	Base Case	**EE Case**	**% Change**
Lifetime [yr]	15	10	-50
E_{emb} [MJ/yr]	3	10	66
E_{dir} [MJ/yr]	1,472	1,098	25
C_{rep1} [$/year]	1	8	88
Price of Energy [$/MJ]	$0.023		
ε [-]	0.0169		
ϒ [-]	0.828		
Re_{dev} [%]	7.1		
Re_{Ew} [%]	26		

Table J. 4: Contributions to Economy-Wide Rebound for Hybrid Automobiles

	Re [%]	**Φ [-]**
Device	7.1	0.276
Embodied	1.7	0.066
Respending	16.9	0.658
Economy Wide	26	1

Analysis

Device 1: Advanced power strips

The data in Table J1 shows that replacing a basic power strip with an APS provides a 25% reduction in energy consumption. After accounting for economy-wide rebound, the economy-wide savings is reduced to 19%. Table J2 shows that the largest contribution to the economy-wide rebound for the APS was the re-spending effect at 65%. Even though the replacement cost increase was very large, the re-spending effect still dominated because the device-level rebound and rebound due to embodied energy changes were both very small.

Device 2: Hybrid cars

The data in Table J3 shows that switching from a gas car to a non-plug in hybrid car produces an economy-wide rebound of 40.28% where the hybrid itself produces a 20% device-level rebound. The most significant contributor to economy-wide rebound was device-level rebound, but only by 1% more than the re-spending effect. It is interesting to note that there is almost no rebound from the process of making the car. This is because the additional embodied energy from the electric motor and battery is small compared to the total embodied energy of the vehicle.

Conclusion

Both device-level and economy-wide rebound for the APS were quite low, indicating that implementing APS should be an effective means of reducing energy usage. Hybrid automobiles, however, have significantly higher device and economy-wide rebounds that make them less attractive as an energy saving intervention. Despite this, the amount of potential energy savings is still large because of the magnitude of the overall energy usage.

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Appendix K: Computer Monitors and Gas Engines

Team D: Tyler Johnson, Christopher Pappageorge, Trevor Sando

Dr. Heun and Dr. Brockway

Engineering 333: Thermal Systems Design

December 18, 2019

Introduction

Over the past several months, the Engineering 333 class at Calvin University has been conducting research with the goal of determining the economy-wide rebound effect of adopting new energy efficient technologies. The students in this class were grouped into teams, with each team researching the rebound effect of two different energy efficiency interventions. In this report, the results of the studies done by Team D on the economy-wide rebound effect of computer monitors and gas-powered automobiles are discussed.

Computer monitors are used in nearly every office, academic building, and library in the United States, and many of the monitors still in use are older outdated screens that consume far more power than the newer improved models. For this study, the Dell E198WFP model from 2008 is used as the base case device, chosen because it is one of the monitor styles that are used in the Engineering Reading and Reference room (SB 136). The energy efficient device was chosen to be the Dell E1911, an updated model of the E198 from 2010, because it has nearly the same specifications as the base case while consuming significantly less energy. Both are standard 19" monitor displays with the same surface area and are assumed to be at the same brightness.

Gas-powered automobiles were chosen using the following conditions: both automobiles run on gasoline only, both are as similar as possible, and one of the two models is significantly more efficient than the other. The chosen models are the Honda Accord V6 2017 and the Honda Accord LX 2017. These two models meet the conditions since they both run on solely gasoline, they share the same shell and interior, and the LX is much more efficient then the V6 model.

Methods

Device 1: Computer Monitors

The values found in the calculations for economy-wide rebound from the effect of computer monitors can be found in Table 2. The price of energy is defined as the amount that Calvin University pays for its energy, and the cost of replacement is the sum of the cost of the monitor and the cost of recycling (Select Items to Recycle) divided by the monitor's lifetime (Robertson, 2010).

The embodied energy of the base case monitor was determined by calculating the surface areas of the monitors from their user manuals and then multiplying those areas by the square meter embodied energy costs of LCD screens (Jonbrink, 2007). As both screens are the same size, the energy efficient case's embodied energy was found by multiplying the ratio of the weights of the two monitors to find the embodied energy of the energy efficient case (Dell E19 user manuals were used to reference the weights). This number was validated because these values were between the embodied energy costs found for 17" (Jonbrink, 2007) and 20" (Moshnyaga, 2008) monitors from the same time period.

The direct energy was an estimation based off assumptions of usage, shown below in Table 1. This results in 1260 hours each year with the monitor being used, and 7500 hours a year with the monitor on "power-save mode." These hours are then multiplied by the power consumption of the monitor found in their user manuals to obtain the Table 2 values.

Table K. 1: Monitor Utilization Assumptions

Weeks/year	30 Weeks	18 Weeks	4 Weeks
Days/week on	6	5	0
Hours/day on	6	2	0

The device-level rebound was assumed to be 0%, as updating a monitor to a newer model would not have an impact on how much usage the monitor would have. With all the initial values found, the series of calculations in Appendix A1 was used to find rebound effects at all stages.

Device 2: Gas-powered Automobiles

To calculate the economic rebound there were three main values for each case that had to be found. The first value that was calculated was the cost of the device over its lifetime on a yearly base. This includes maintenance, fuel, and price of automobile spread across over the lifespan. (Kelly Bluebook, 2019a&b) Every lifetime calculation is based on the group consensus of a 12 year life of the car and that each car drives 15,000 miles each year. Also, based on research [13][14] that the price of gas would be $2.69/gal, and the energy in each gallon of gas is 127 MJ. The second major value that was calculated is the embodied energy. Due to the lack of literature on this specific model the embodied energy was estimated. Using estimated material compositions of class D sedans (Dai, Kelly and Elgowainy, 2016) the amount of each material was found using the weight of the vehicle. Once the total amount of each material was known, the embodied energy of each material was totaled into the embodied energy of the car. The last major variable that was calculated is the energy directly consumed by the vehicles. This was done by taking the total miles driven in a year (mi/yr) and dividing by the fuel efficiency (mpg), then multiplying by the energy in each gallon (MJ/gal). This yielded the total energy consumed each year (MJ/yr). With these numbers, combined with the device-level rebound, the calculations for economic rebound were conducted, yielding the results seen in Table 3.

Results

Table K. 2: LCD Monitor Calculation Parameters

	Base Case	**EE Case**	**% Change**
Lifetime [yr]	10	10	0
E_{emb} [MJ/yr]	112	105	-7
E_{dir} [MJ/yr]	226	104	54
C_{rep1} [$/year]	9	12	21
Price of Energy [$/MJ]	$0.023		
ε [-]	-0.0623		
ϒ [-]	0.903		
Re_{dev} [%]	0.0		
Re_{Ew} [%]	10		

Table K. 3: LCD Monitor Contribution to Energy-Wide Rebound Effect

	Re [%]	Φ [-]
Device	0	0
Embodied	-6.3	-0.63
Respending	16.3	1.63
Economy Wide	10	1

The LCD monitor's 10% contribution to economy-wide rebound is dominated by the re-spending term. As its device-level rebound is zero and the epsilon term contributes opposite of the economy-wide rebound (under the assumption that the base case should have less embodied energy than the energy efficient case, which does not hold true here), the re-spending term is the sole positive contributor to the economy-wide rebound at +16%.

Table K. 4: Honda Accord 2017 Calculation Parameters

	Base Case	EE Case	% Change
Lifetime [yr]	12	12	0
E_{emb} [MJ/yr]	10,516	9,406	-12
E_{dir} [MJ/yr]	70,556	56,029	21
C_{repl} [$/year]	2,944	2,803	-5
Price of Energy [$/MJ]	$0.021		
ε [-]	-0.0764		
ϒ [-]	-0.460		
Re_{dev} [%]	6.0		
Re_{Ew} [%]	217		

Table K. 5: Honda Accord 2017 Contribution to Energy-Wide Rebound Effect

	Re [%]	Φ [-]
Device	6.0	0.028
Embodied	-7.6	-0.035
Respending	218.3	1.007
Economy Wide	217	1

The base case vehicle weighs more thus from the calculations the embodied energy would be more than that of the energy efficient case. The change cost of replacement is negative because the price of the base case vehicle is less than that of the energy efficient case. Because of the similarity in the vehicles the rebound due to embodied energy is smaller and helps to reduce the total economic rebound. However, the re-spending term dominates the cost to the economy.

Analysis

An economy-wide rebound of 10% means that only 90% of the energy savings that are expected from changing to the energy efficient case are realized. However, this is still a very good tradeoff, as the energy efficient monitor uses less than half of the direct energy of the base monitor, so changing to this device still saves a considerable amount of energy. Additionally, 10% is not a significant number compared to many of the other devices seen in this study, but considering that monitors are ubiquitous in the workplace, schools, and the home, this 10% economy-wide rebound for every monitor can quickly become a noteworthy factor.

An economy-wide rebound of 10% means that only 90% of the energy savings that are expected from changing to the energy efficient case are realized. However, this is still a very good tradeoff, as the energy efficient monitor uses less than half of the direct energy of the base monitor, so changing to this device still saves a considerable amount of energy. Additionally, 10% is not a significant number compared to many of the other devices seen in this study, but considering that monitors are ubiquitous in the workplace, schools, and the home, this 10% economy-wide rebound for every monitor can quickly become a noteworthy factor.

For device 2 the economy-wide rebound is shown to be 217%. This means that of the expected savings (the savings of just fuel efficiency) the economy will consume all those savings times 2.17, thus consuming much more energy then was meant by switching to a more efficient alternative. This is because the energy efficient case is cheaper in every regard. This allows the buyer to save a lot of money and spend that money elsewhere.

Conclusion

The goal in analyzing these devices was to determine the economy-wide rebound caused by each device change. Both devices investigated in this study – the low-cost LCD monitors and the more expensive gas automobiles – resulted in economy-wide rebound but through vastly different contributing factors and with significantly varied rebound numbers. Switching to the efficient case caused a 10% economy-wide rebound for the monitors and a 216.7% for the automobiles. Thus, switching monitors will affect the economy about as much as one would expect. Switching automobiles, on the other hand, will affect the economy far more and result in additional energy saving which causes a backfire effect in the economy.

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