Solar-Powered Traffic Light

ECE 445 Design Document - Spring 2022

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Team 20

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1 Introduction

1.1 Problem

Traffic lights are integral to our society, despite their relative lack of innovation over the years. The most significant change has been the switch from incandescent bulbs to LEDs in an attempt to reduce the power consumption of this necessary device. However, this has also led to an increase of light pollution due to the cooler, more intense light emitted by LEDs. They can cause extreme glare and pose a danger to drivers at night. Additionally, the issue of bicyclists and vehicles sharing the road can create many awkward or dangerous situations due to the lack of separation.

1.2 Solution

We propose a solar-powered traffic light system that will reduce light pollution and solve the issues of drivers and bicyclists sharing the intersection. Solar power will operate the system to minimize utility power used during the day. Connection to the grid is necessary for operation at night or when solar conditions are suboptimal. At night, pulse-width modulation (PWM) circuitry will dim the LED modules. This not only reduces light pollution, but also lowers utility consumption at night. In the case of adverse weather conditions, the system should not dim the lights to ensure proper visibility. Pedestrians and cyclists can alert the system of their presence by pressing a button and cross the intersection once their respective lights signal to do so.

1.3 Visual Aid

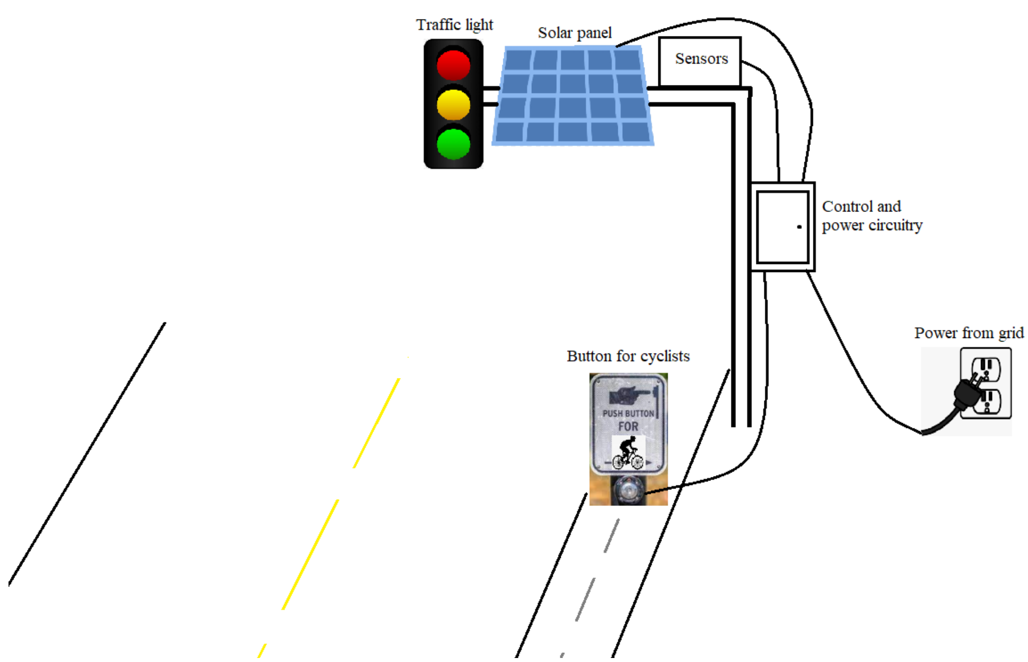

Figure 1: Visual Aid

1.4 High-level Requirements List

- In order to limit light pollution and reduce consumption of utility power, the light modules must use PWM to operate with less power when it is sufficiently dark outside (assuming clear weather). We estimate our entire system to use approximately 22 watts of power, compared to a regular traffic light system with 3 LED bulbs which uses about 45 watts of power [1]. Should the power saved over an expected lifespan of about 20 years be greater than the initial cost of this system (and the other two requirements are met), we can conclude that this system is a success.

- The system must be able to switch between solar and utility power without causing a power failure. This is especially important when switching to utility power at night.

- The system must be able to efficiently adjust the light patterns and lengths of operation to increase the efficiency of traffic. Bicyclists and pedestrians can press one of two buttons to trigger the bicycle and walk signs for them to safely cross the intersection. Assuming a walking pace of 3 miles an hour and a lane width of 20 feet [2], the walk signal must be on for a minimum of 15 seconds to ensure everyone crosses.

2 Design

2.1 Block Diagram

Following is a block diagram of our system comprised of four subsystems: Sensing, Control, Power, and Traffic Light. Pictured in each subsystem are the components that make up the subsystem. The arrows represent connections between each subsystem. Follow the legend on the right to see what each arrow represents.

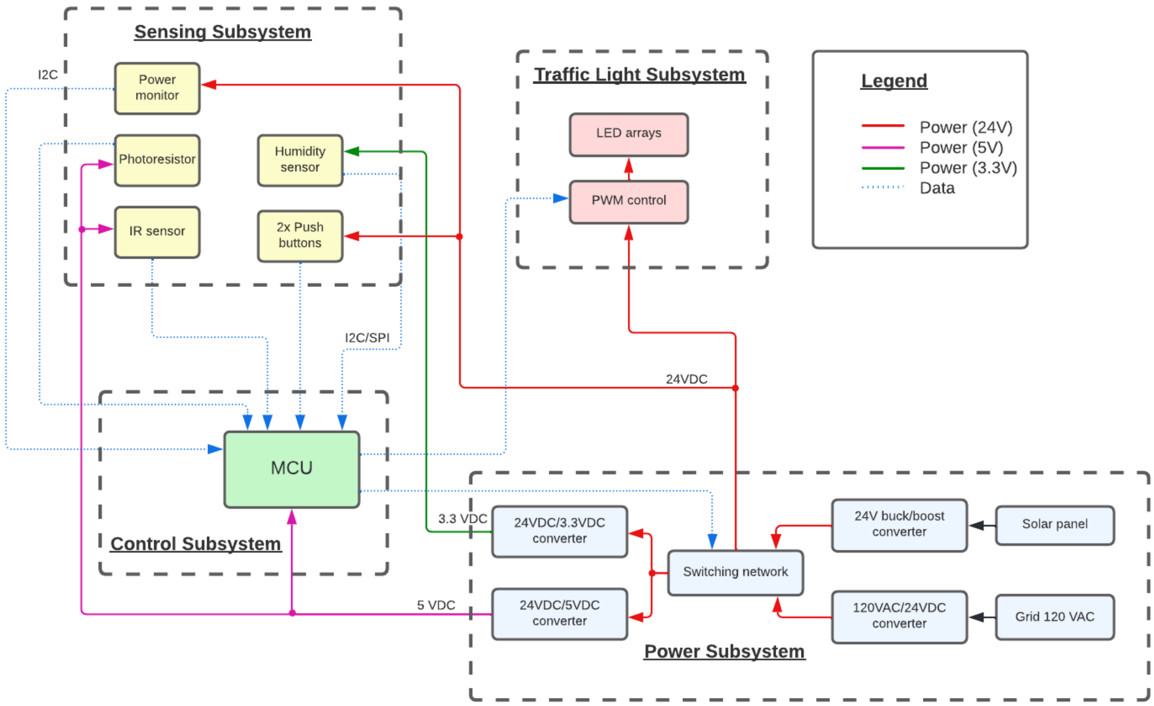

Figure 2: Block Diagram

2.2 General System

Our system as a whole will consist of a power subsystem, sensing subsystem, control subsystem, and traffic light subsystem. The heart of the system is the control subsystem, which consists of microcontroller that takes input from the sensing and power subsystems and sends control signals to our traffic light subsystem and power subsystem. The signal to the traffic light subsystem will control the PWM circuitry that determines the brightness of our LED traffic lights. The signal to our power subsystem, based on readings from our power monitor, will control the switching network and decide when to draw power from the solar panel versus the grid.

Requirements	**Verification**
The system enclosure must be rainproof, up to about 3.5 inches monthly - the average precipitation based on the 1981 to 2010 averaging period [3].	1. We can simulate this by assuming our enclosure area to be 1ft x 3ft x 1ft and spraying approximately 2 gallons of water on it.

2.3 Power Subsystem

2.3.1 Solar Panel

Main power will be supplied by a solar panel with an output voltage of 18V.

Requirements	**Verification**
The solar panel must provide a minimum of 40W.	1. Use two multimeters and connect one in series with a power resistor and one in parallel across the power resistor to measure current and voltage, respectively. 2. Multiply current and voltage readings to get power output, which should be 40W $\pm$ 20% on a cloudless and sunny day.

In full sunlight, the panel must generate 18V±5% when loaded.	1. Program microcontroller with unit test that turns on two light modules at 100% duty cycle. 2. Use a multimeter to take a voltage reading across the solar panel terminals and verify it is within 17.1 V and 18.9 V.

2.3.2 Power Converters

Voltage converters regulate the various voltage levels required in each subsystem. A single-ended primary-inductor converter (SEPIC) converts the solar DC output of 18 V ± 5% to the 24 V required for the overall system. Figures 3 and 4 demonstrate the circuit diagram and output waveform for the SEPIC converter.

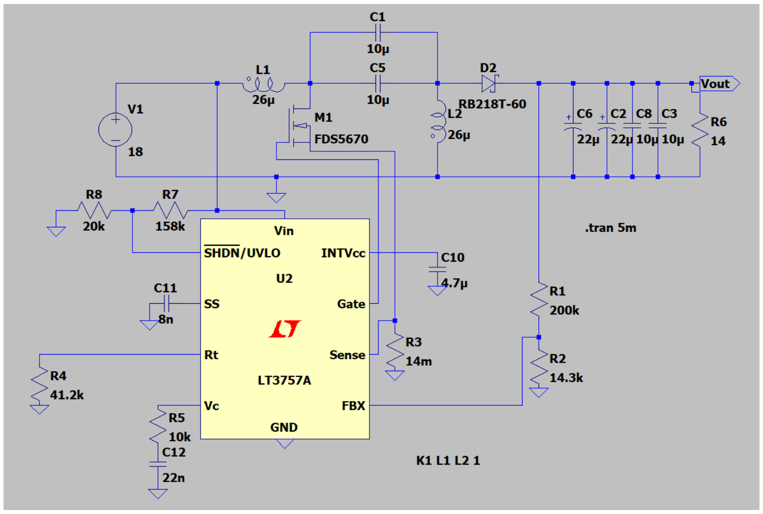

Figure 3: 24 V SEPIC converter schematic

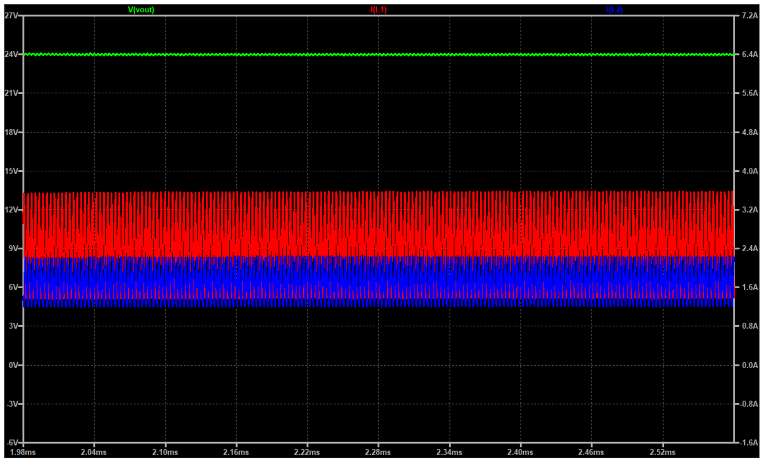

Figure 4: 24 V SEPIC converter simulation - 24 V output (green), inductor currents (red and blue)

When the solar power is insufficient, the system must switch to AC utility power. An AC/DC converter converts this 120 VAC voltage to the required 24 VDC.

A common 24 V bus is downstream of both this converter and the SEPIC converter, at which point the traffic lights are powered and the remaining converters regulate 3.3 V and 5 V for the control and sensing subsystems. Figures 5 - 7 demonstrate the voltage regulator circuits, 3.3 V simulation, and 5 V simulation, respectively.

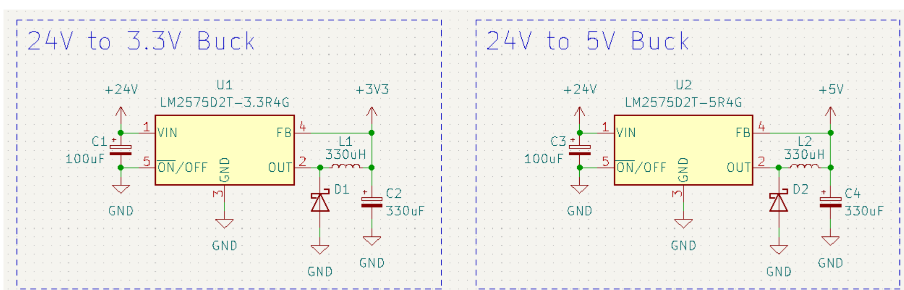

Figure 5: 3.3V and 5V buck converter schematic

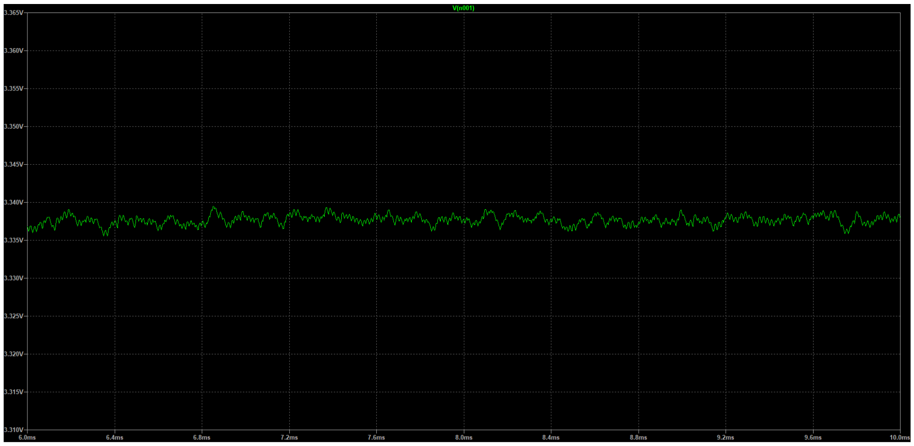

Figure 6: 3.3V buck converter simulation

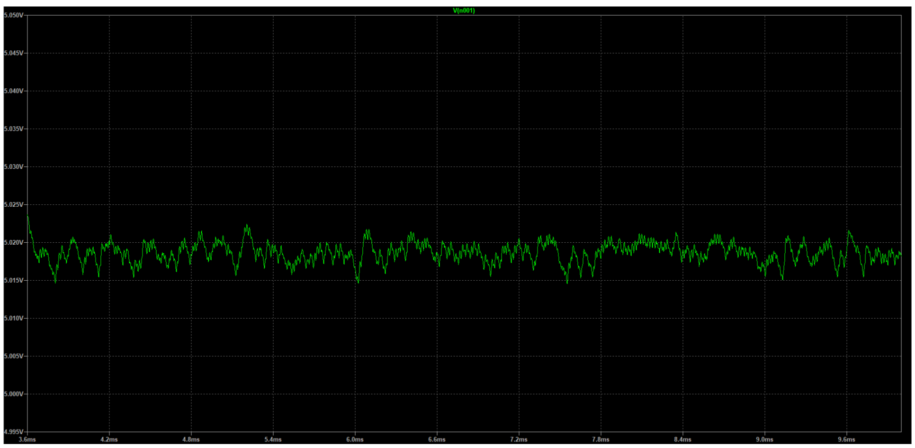

Figure 7: 5V buck converter simulation

Requirements	**Verification**
The SEPIC converter at the solar output must provide 24 V ± 5% at up to 1.7 A output current for 12 V ≤ V_{in}≤ 32 V.	1. Use an oscilloscope and a multimeter to check that the output is 24 V ± 5% and up to 1.7A, respectively. Sweep the input voltage between 12 V and 32 V with the DC power supply at the work station.
The AC-DC converter at the grid output must convert 120 V ± 10% to 24 V ± 5% at up to 2 A output current.	1. Use power supply to vary the input from 108 VAC to 132 VAC and use a multimeter to ensure output remains within desired bounds.
The 24 V to 5 V converter must provide 5 V ± 5% at up to 500 mA output current.	1. Use DC power supply to vary the input from 21.6 V to 26.4 V and use a multimeter to ensure output remains within desired bounds.
The 24 V to 3.3 V converter must provide 3.3 V ± 5% at up to 500 mA output current.	1. Use DC power supply to vary the input from 21.6 V to 26.4 V and use a multimeter to ensure output remains within desired bounds

2.3.3 Switching Network

The switching network switches the input source seamlessly between solar and utility power. It will prioritize using solar power and only switch to utility power if solar power drops below a threshold of 20 W, at which point the control subsystem will alert the switching network.

Requirements	Verification
Switching between the two sources must not interrupt normal operations.	1. Program the microcontroller to switch between power sources every 10 seconds and a counter. 2. Use an oscilloscope to verify that the 24 V, 5 V, and 3.3 V rails remain within tolerance levels. 3. Visually monitor lights and ensure no flickering occurs. 4. Check to make sure counter does not reset after any switches. If it does, the microcontroller temporarily lost power due to the switching.
Switching transients must not exceed 2.4 V.	1. Measure output voltage using an oscilloscope to ensure that it stays within 10% of 24 V every time the input switches.
Switching time must not exceed 20 ms.	1. Connect an oscilloscope to the gates of each pair of MOSFETs in the switching network to ensure the one pair turns on within 20 ms of the other pair turning off.

2.4 Sensing Subsystem

The sensing subsystem contains all sensors used in the system: one for power monitoring and the rest for the traffic lights. A current/voltage sensor is used to determine the output power of the solar panel. The power value is sent to the control subsystem using the I2C protocol. If the solar panel is disconnected, its power can still be measured through a dead load consisting of a power resistor at the output of the SEPIC converter.

The traffic light sensors include two buttons, a light dependent resistor (LDR), a humidity sensor, and an infrared sensor. The buttons determine if there are bikes or pedestrians waiting to cross the street. Realistically, the wires carrying the button signals would be 20+ feet long, so a 24 V signal will be used to reduce noise interference from voltage drops and ensure signal integrity. An opto-isolator circuit will be used to transmit the 24 V signal to the microcontroller. The LDR is responsible for detecting the presence of sunlight and sending a signal to the MCU. Its resistance can range from a few hundred ohms in a bright environment to over one mega ohm in complete darkness. A simple voltage divider circuit will be used to correlate the light level to voltage level. The humidity sensor is used to detect adverse weather conditions and turn off the PWM light dimming if it is on. This ensures proper visibility of the traffic lights. The infrared sensor is used to detect vehicles and send a signal to the microcontroller.

The sensors cumulatively draw less than 400 mW of power. The humidity sensor operates at 3.3 V and 980 μA [4], current and voltage monitor at 24 V and 1.2 mA [5], light dependent resistor dissipates 2.5 mW on a bright day [6], and the IR sensor at 5 V and up to 50 mA [7]. We assume the button and opto-isolator to dissipate 70 mW [8].

Requirements	**Verification**
1. The power monitor must be accurate to ±5% of the actual wattage. 2. The power resistor must not exceed the rated operating temperature of 25°C (at 140 W) while dissipating power [9].	1. Use two multimeters and connect one in series to the power resistor and one in parallel across the power resistor to measure current and voltage, respectively. Multiply values to compute power and ensure the power monitor reading is within 5%. 2. Use a laser thermometer to check temperature of the resistor. If the temperature is above 25°C under full load, we will attach a passive heat sink on the resistor's base plate to prevent overheating and performance degradation.

1. The buttons must not shock anyone who touches it. 2. The signal must be transmitted across the opto-isolator within 1 ms.	1. Use an multimeter to ensure the enclosures and buttons themselves are properly grounded. Visually inspect all wires for proper insulation and exposed copper. 2. Use an oscilloscope and connect a probe to the button and another to the opto-isolator output pin. The time between the button press and opto-isolator output time must be below 1 ms.
The LDR must be able to differentiate between various light intensities.	1. Measure the voltage divider output voltage when the system is exposed to the sun at noon, complete darkness, and a dimly lit room.
The IR sensor must be able to detect the presence of a vehicle from a distance of 10 ft to 18 ft.	1. Position the sensor 10ft and 18ft (maximum range) away from a vehicle and measure corresponding output voltages. 2. Compare the voltage levels and establish a lower and upper boundary. 3. Program the microcontroller with a test program to indicate if the voltage is within the boundary (i.e. car detected).

2.5 Control Subsystem

2.5.1 Control Flow

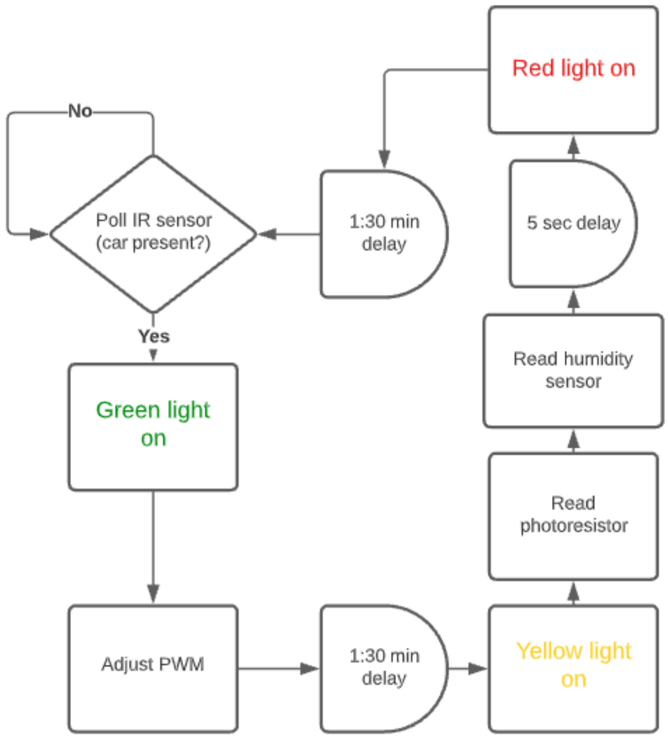

Figure 8: MCU control flow

In addition to the main control flow, when a biker or pedestrian presses their respective button, it will generate an interrupt. At this time the state of the lights will be checked and the lights will begin to change red or stay red and allow the biker/pedestrian to cross.

2.5.2 Microcontroller

The microcontroller, the ATmega328-PU, takes data from the various sensors and controls the PWM for the LEDs, the timing for the traffic lights, and the switching network in the power subsystem.

Requirements	Verification
Microcontroller must respond to button interrupts within 5 ms. Note that this requirement is different than the signal reaching the microcontroller within 1 ms.	1. Program a unit test that toggles a GPIO pin when a button interrupt is received. The traffic light FSM must be running when pressing button. 2. Use an oscilloscope and connect a probe to the button and another to the microcontroller GPIO pin. The time between the button press and microcontroller GPIO toggle time must be below 5 ms.
Microcontroller takes sensor feedback and responds with appropriate control signals (PWM and switching power sources).	1. Perform experiment in a room with dimmable lights. Program microcontroller to change PWM duty cycle linearly based on light intensity. Use an oscilloscope on the PWM pin and dim the lights. The duty cycle should decrease from what it was initially 2. Hook up an oscilloscope to the gate of one MOSFET from each pair of MOSFETs in the switching network (see Figure 9). Ensure that the solar panel powers the system (power output above 20 W). The MOSFET gate of the solar power portion should be high and of the grid portion should be low. Cover the solar panel with a cloth such that the power output drops to below 20 W and verify that the MOSFET gate of the solar portion is low and the grid portion is high.

2.6 Traffic Light Subsystem

For our traffic light system we will be constructing them out of high power LEDs, which we will have to design an additional PCB board for or get a sample of real traffic lights to use in our project.

Requirements	Verification
1. The LEDs must be visible from 150 ft for drivers to see them in bright conditions. Most modern traffic lights are 400-1000 lumens so we aim to be in this range [10]. 2. The LEDs should have multiple dimming levels (i.e. 40%, 60%, 80%, and 100% of full brightness), achieved by changing the PWM duty cycle to corresponding percentages. 3. The PWM frequency must be above 80 Hz, the maximum flicker frequency that is visible to the human eye [11].	1. Stand 150 ft away and see if the lights are visible. Use a light meter to measure lumen output and ensure it is within 400-1000 lumens. 2. Use an oscilloscope to ensure the PWM duty cycle is within 5% of expected percentage. Use light meter to correlate 100% duty cycle to maximum brightness. Measure lumen output with a light meter at multiple levels and ensure they are within 5% of expected brightness level. 3. Use an oscilloscope to verify that the PWM circuit oscillates at a minimum of 80 Hz.

2.7 Tolerance Analysis

The main issue we will run into for this project is creating a 24 V switching network. We will need to ensure there is no delay or outage in our traffic lights when switching between grid power and solar power. Specifically, we aim to minimize the transient voltage to below 2.4 V and switching speed below 20 ms. For this, we will use an LT1161, which can be used to OR power sources. If the output voltage transient is above the threshold, we can use capacitors to smooth the waveform.

The switching network consists of 4 high-side MOSFETs and a gate driver that takes inputs from the control subsystem. Figures 9 and 10 demonstrate the switching network schematic and its simulation, respectively. In simulation, the voltage drops to about 23.6 V when the input switches from one to another. Since the MOSFET gates will be controlled by the microcontroller, the rise and fall times of the GPIO pins are important. From the ATmega328 datasheet [12], the maximum rise/fall time of any pin is 1600 ns. This means that the switching network can successfully switch between solar and grid power while reducing transients and switching speed.

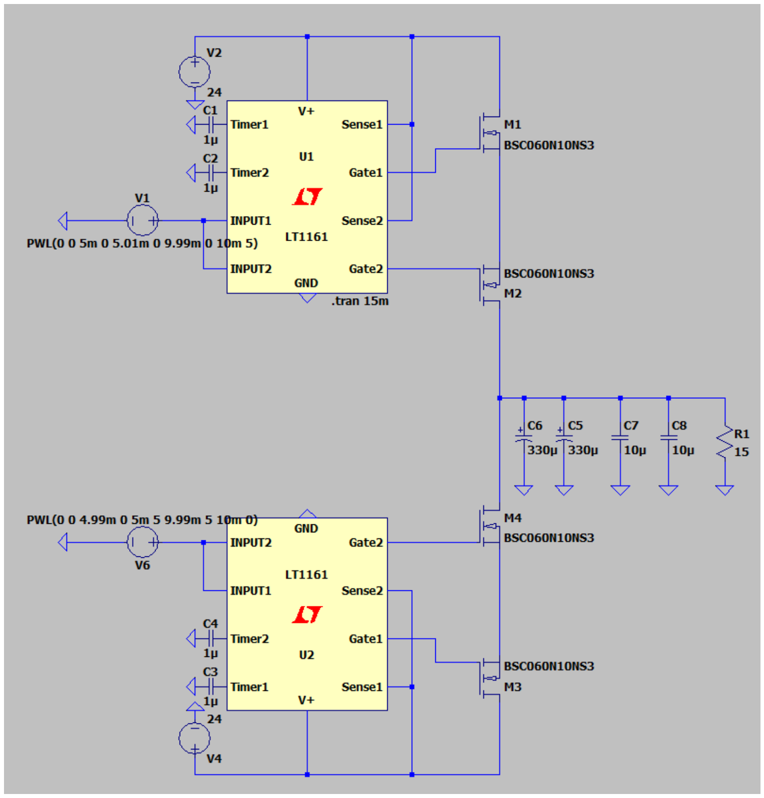

Figure 9: Switching network schematic

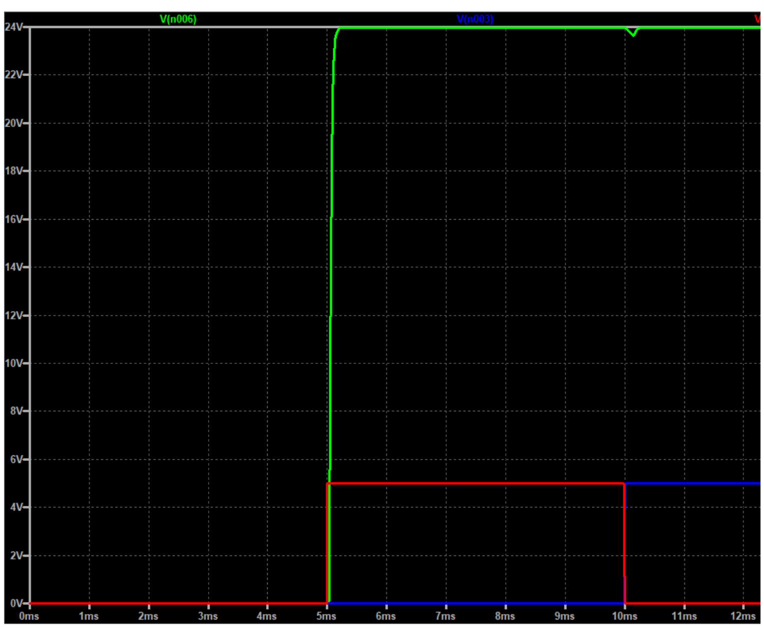

Figure 10: Switching network simulation - Source turned on at 5 ms and switched from solar (red) to grid (blue) at 10 ms

3 Cost and Schedule

3.1 Cost Analysis

3.1.1 Labor

Our team consists of two electrical engineering majors and one computer engineering major. From the 2019-2020 annual Illini Success Report, electrical engineers make an average of $76,129 and computer engineers make an average of $99,145 [13]. There are 9 weeks left in the semester, and we will work approximately 10 hours per week. This will total 90 hours. We will also multiply by a 2.5x overhead cost.

Name	Bowen Xiao	Richard Przybek	Colin Tarkowski
Rate	$38.06	$49.57	$38.06
Hours worked	90	90	90
Total Cost	$8563.5	$11,153.25	$8563.5

3.1.2 Parts

Following is a table of all the parts required for the project and their associated costs.

Component	**Part #**	**Quantity**	**Unit Price**	**Total Price**
3.3 V Buck IC	LM2575D2T-3.3R4G	1	$2.26	$2.26
5 V Buck IC	LM2575D2T-5R4G	1	$2.84	$2.84
Schottky Diode	VS-30WQ04FNTR-M3	1	$0.68	$0.68
300μH Inductor	HCTI-330-5.2	1	$2.99	$2.99
140W Resistor	TEH140M33R0FE	1	$15.20	$15.20
AC/DC Converter	LM100-23B24	1	$17.44	$17.44
Power Monitor	LTC4151IMS-1	1	$8.40	$8.40
Optoisolator	MOCD207M	2	$1.30	$2.60
Sense Resistor	ERJ-3BWFR020V	1	$0.45	$0.45
Pushbutton	GPTS203211B	2	$1.71	$3.42
Photoresistor	161	1	$0.95	$0.95
Humidity Sensor	DHT20	1	$6.50	$6.50
IR Sensor	GP2Y0A710K0F	1	$21.21	$21.21
MCU	ATMEGA328-PU	1	$2.58	$2.58
Coupled Inductor	PF0553.153NLT	1	$2.54	$2.54
MOSFET	FDS5670	1	$1.82	$1.82
14 mΩ Sense Resistor	WSL2512R0140FTB	1	$2.21	$2.21
Schottky Diode	SBRT10U60D1-13	1	$0.97	$0.97
SEPIC Controller	LT3757AIMSE	1	$6.69	$6.69
MOSFET	FDD8453LZ	4	$1.51	$6.04
Quad High-Side Gate Driver	LT1161IN	1	$9.91	$9.91
Resistors and Capacitors	N/A	N/A	N/A	$8.00
			Total Cost	**$125.70**

3.2 Schedule

Week	Bowen	Richard	Colin
2/21	Complete design document Design document review	Complete design document Design document review Follow up on Leotek samples	Complete design document Design document review
2/28	Work on getting PCB board approved	Put together list of parts for ordering Submit order for parts from machine shop	Work on getting PCB board approved
3/7	Work on physical design of lighting enclosure Work on programming the MCU	Work on physical design of the lighting enclosure Work on programming the MCU	Work on physical design of the lighting enclosure Talk to machine shop and have them start to make it
3/21	Start assembling and soldering PCB board and debug any subsystems/issues	Complete software for the MCU and begin testing Integrate the MCU with the rest of the hardware	Start assembling and soldering PCB board and debug any subsystems/issues
3/28	Complete individual progress report Perform overall testing of the system	Complete individual progress report Perform overall testing of the system	Complete individual progress report Perform overall testing of the system
4/4	Create mock demo	Create mock demo	Create mock demo
4/11	Create mock demo. Start working on final paper.	Create mock demo. Start working on final paper.	Create mock demo. Start working on final paper.
4/18	Mock demo. Begin working on final demo	Mock demo. Begin working on final demo	Mock demo. Begin working on final demo
4/25	Final demo. Create mock presentation.	Final demo. Create mock presentation	Final demo. Create mock presentation.
5/2	Final presentation. Submit final paper and lab notebook.	Final presentation. Submit final paper and lab notebook.	Final Presentation. Submit final paper and lab notebook.

4 Discussion of Ethics and Safety

The team will strive to adhere to the IEEE Code of Ethics. Since we are designing a product for use in traffic, we must ensure “the safety, health, and welfare of the public” and to “disclose promptly factors that might endanger the public or the environment” [14]. The team will be transparent with all design choices and will not falsify any data or make misleading claims.

Although our design will be a scale model of a real traffic light system, we will not be adhering to the building codes within the city of Champaign and our traffic light will not be put to use in any real traffic on streets. We will, however, meet the relevant requirements, laid out in the city of Champaign Traffic Signal Standards, for our scale model. Specifically we will try to incorporate requirements b, e, f, and h under the section labeled *Traffic Signal Requirements*. As well as requirements a, f, and h from the section labeled *Electrical Requirements*. For example, requirement h states that “power disconnects shall be provided” [15]. In the case of emergency, both the solar panel and grid will be able to be physically disconnected from the rest of the system.

For the purposes of prototyping and due to our limited budget we will only be making a single traffic light. Our demonstration will feature traffic flowing in only one direction. We will not concern ourselves with the control required for multiple switching traffic lights, as we will be unable to demonstrate this functionality with only one light. In reality our design will be meant for a traditional four-way intersection, our system should be clonable for each direction not shown in our demonstration, although, it will not feature the timing control of a multiple light system. For our design to be expanded safely to a four-way intersection, a timing control system would need to be incorporated in the future. We will not purposely program any unclear signaling or lower pedestrian/bike crossing times to dangerous levels in order to ”avoid harm” as stated in 1.2 of ACM Code of Ethics [16].

One of the dangers to this project is the bike and pedestrian buttons. Since they will be using 24V to transfer signals, the enclosure must be properly grounded or insulated to minimize risk of electric shock. Additionally, only the ground wire will be extended to the physical switch so that no accidental short circuits will occur. All of the electrical components will be put in a waterproof enclosure with only relevant wires coming out of it. This minimizes the risk of hazardous weather damaging our system and taking the traffic light offline, thus causing confusion.

We will also follow Section 4.1.1 “Relationship between Signal Timing and Traffic Control Design” of the U.S. Department of Transportation’s guidelines for the traffic signal design process [17]. In order to provide the highest level of service to its users, the team will tune the system. Visibility, vehicle detector position, and minimum green time are some of the parameters that we will experiment with. We will also welcome any criticism as to adhere to IEEE Code of Ethics I.5: “to seek, accept, and offer honest criticism of technical work...” [14].

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