EE155/255 Green Electronics

Introduction
9/25/17

Prof. William Dally
Computer Systems Laboratory
Stanford University

STANFORD ENGINEERING

Announcements

- Review session
  - Fridays 4:30-5:50PM
  - Room 380-380Y
  - Bill’s Office Hours 3:30-4:15PM Mondays
  - Right before class
  - Gates 301 (later moving to Allen 106)

Today's Agenda

- Course Logistics
- Why "Green Electronics"

About the Course

- Philosophy
  - Engineering to benefit society
  - Learn *Engineering Thinking* and *Engineering Methods*
  - Hands-on – learn by doing
- 6 Labs
- Project
- 6 HW Assignments
- 1 Midterm
- 3 Guest lectures

Course at a Glance

No	Date	Topic	HW out	HW in	Lab out	Lab ck	Lab	HW
1	9/25/17	Intro (basic converters)	1		1		Intro to ST32F3	Periodic Steady State
2	9/27/17	Embedded Prog/Power Elect.						
3	10/2/17	Power Electronics - 1 (switches)	2	1	2	1	AC Energy Meter	Power Devices
4	10/4/17	Power Electronics - 2 (circuits)						
5	10/9/17	Photovoltaics	3	2	3	2	PV MPPT	Motor control Matlab
6	10/11/17	Feedback Control						
7	10/16/17	Electric Motors	4	3	4	3	Motor control - Lab/	Feedback
8	10/18/17	Isolated Converters						
9	10/23/17	Solar Day	5/PP	4	5	4	PS	Isolated Converters
10	10/25/17	Magnetics						
11	10/30/17	Soft Switching	6	5/PP	6	5	Magnetics	Magnetics and Inverters
12	11/1/17	Project Discussions						
13	11/6/17	Inverters, Grid, PF, and Batteries		6	P	6	Project	
14	11/8/17	Thermal & EMI						
15	11/13/17	Quiz Review				C1		
16	11/15/17	Grounding, and Debugging						
Q	11/15/17	Quiz - in the evening						
	11/20/17	Thanksgiving Break				C2		
	11/22/17	Thanksgiving Break						
17	11/27/17	Wrapup						
18	11/29/17	Guest Lecture				C3		
19	12/4/17	Guest Lecture						
20	12/6/17	No Class						
	TBD	Project presentations			P			
	12/15/17	Project webpage due						

http://web.stanford.edu/class/ee152/about.html https://piazza.com/stanford/fall2017/ee155ee255

Grading

6 Homeworks	15%
6 Labs	25%
1 Midterms	25%
1 Project	30%
Participation	5%

Collaboration

- May collaborate in groups of up to 4 on homework assignments
  - Turn in one assignment for the group.
  - Give attribution for any outside assistance
- Labs to be done in assigned groups of 3-4
  - Except Lab 1 which is done individually
- Projects may be done in groups of up to 4

Labs

- One lab each week
  - Assigned on Monday (9/25 for Lab 1)
  - Must be demonstrated and signed off during your lab session the following week
- Groups of 3-4 (except Lab 1)
  - If you have partners lined up, put them on your lab sheet
- Lab will be open 7-10pm several nights per week
  - Write down what evenings you are available
  - We will assign you one evening for your checkoff
- Uses an STM32F3 microcontroller
- Clean up after each session

Labs

- Introduction to ST32F3 Microcontroller
- AC energy meter
- PV power-point tracker
- Motor control
- Power Supply
- Magnetics

Project

- Proposal assigned Oct 24 (in parallel with lab 5)
- Project starts Nov 7 (after lab 6)
- Present on TBD
- Web page due by 12/15
- Weekly checkpoints
- Significant investigation related to green electronics….

Candidate Projects

- Efficient power converter
- Novel converter control strategies
- Soft switching
- Converters using SiC and GaN devices
- Inverter
- Power factor correction
- Smart grid control devices
- Battery characterization
- Battery management
- New concept in PV control
- Direct PV to HV AC converter
- Three-phase motor control
- Energy monitoring
- Energy-conservation via control
- Your idea…

One project from 5 years ago

SunPower Acquires Solar Power Electronics Startup Dfly Systems

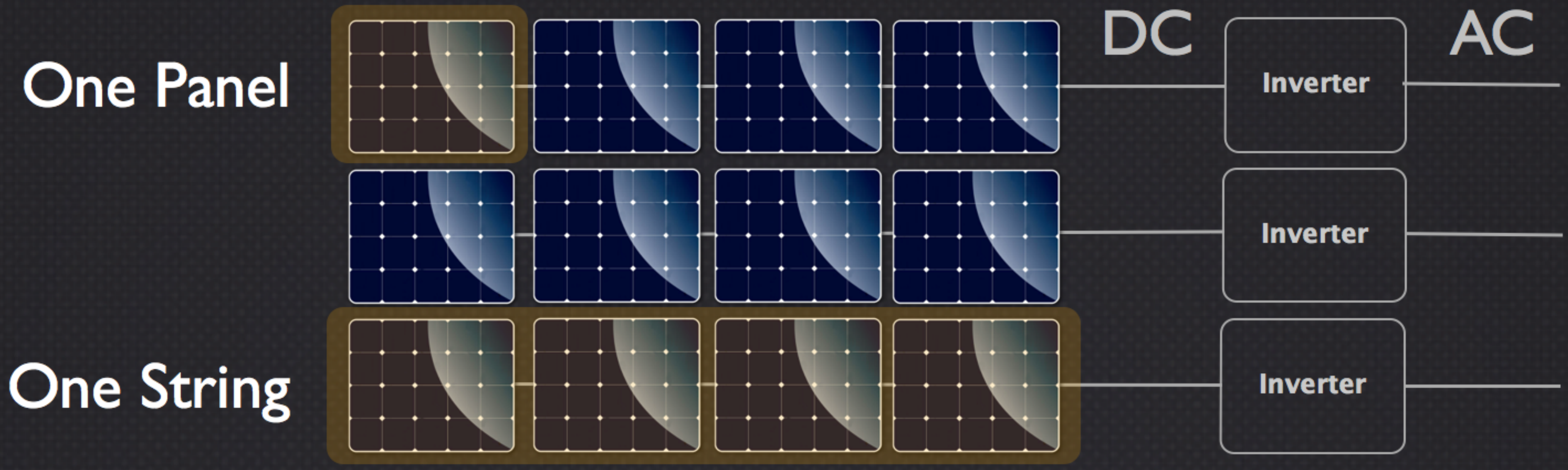
Vertically integrated solar module maker and project developer SunPower buys a Stanford-spawned solar startup.

Eric Wesoff
August 6, 2014

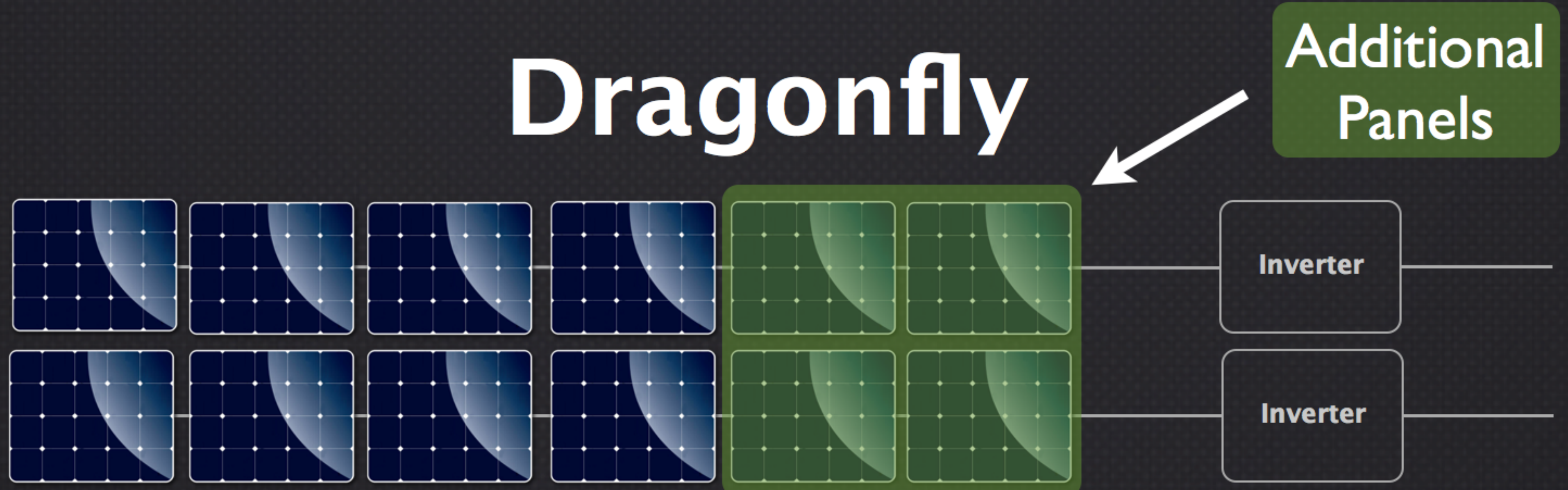
Although not yet announced, GTM has just learned that SunPower has acquired Stanford-spawned, early-stage power electronics firm Dfly Systems, according to sources close to the deal. Pricing was not disclosed. SunPower has confirmed the acquisition.

Details are scant at this point, but the small firm "builds power electronics that lower system costs," according to folks in the know who suggest that the new electronics can replace "traditional and unreliable" bypass diodes while lowering balance-of-system costs. The voltage management technology has the potential to reduce cabling and improve inverter performance, according to our sources.

Conventional



Dragonfly



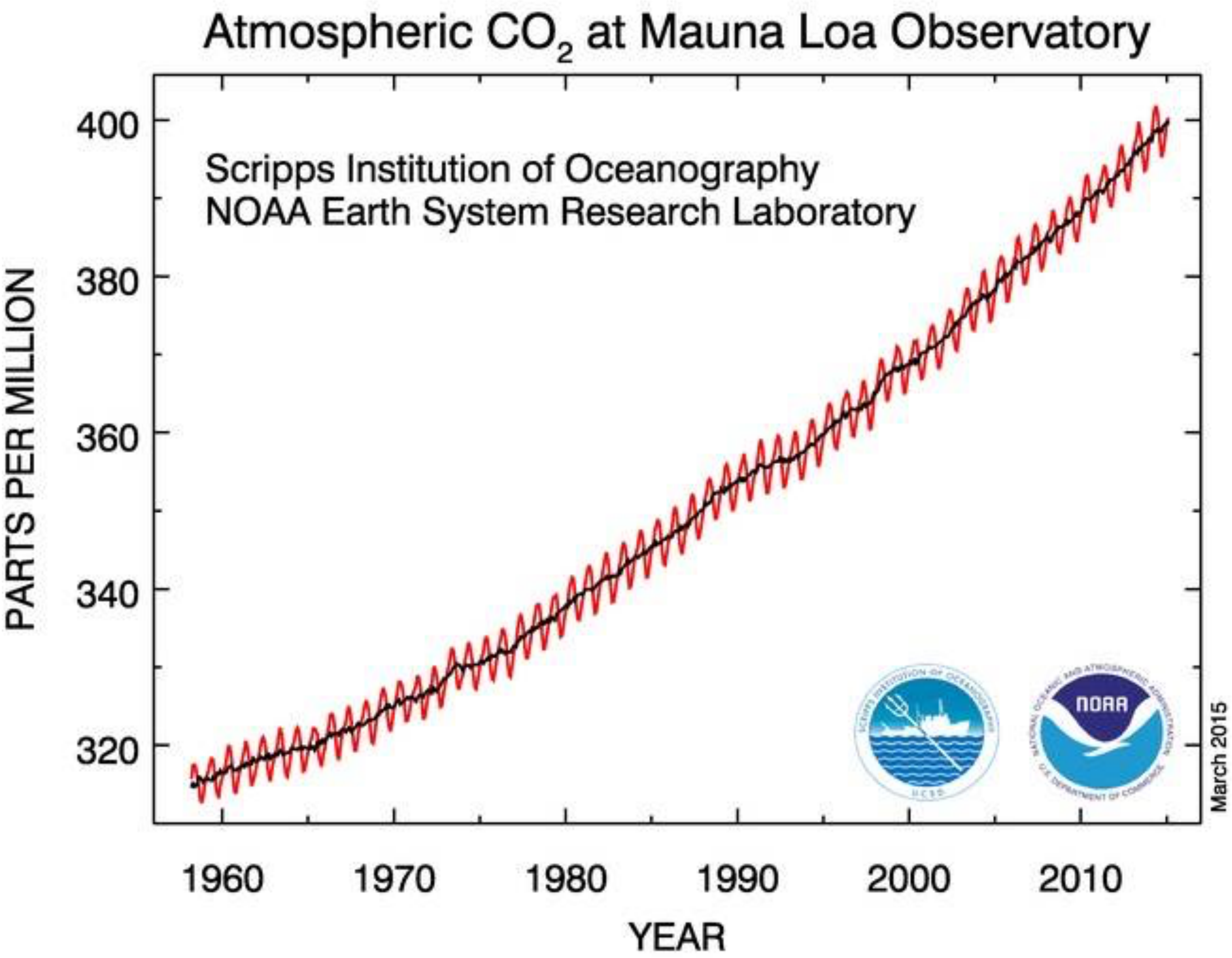
Homeworks

- Assigned each Monday
- Due the following Monday
  - (last chance to turn in on Tuesday morning)
- OK to work in groups of up to 4
  - Turn in one solution and list all who participated
  - Give attribution for any outside help

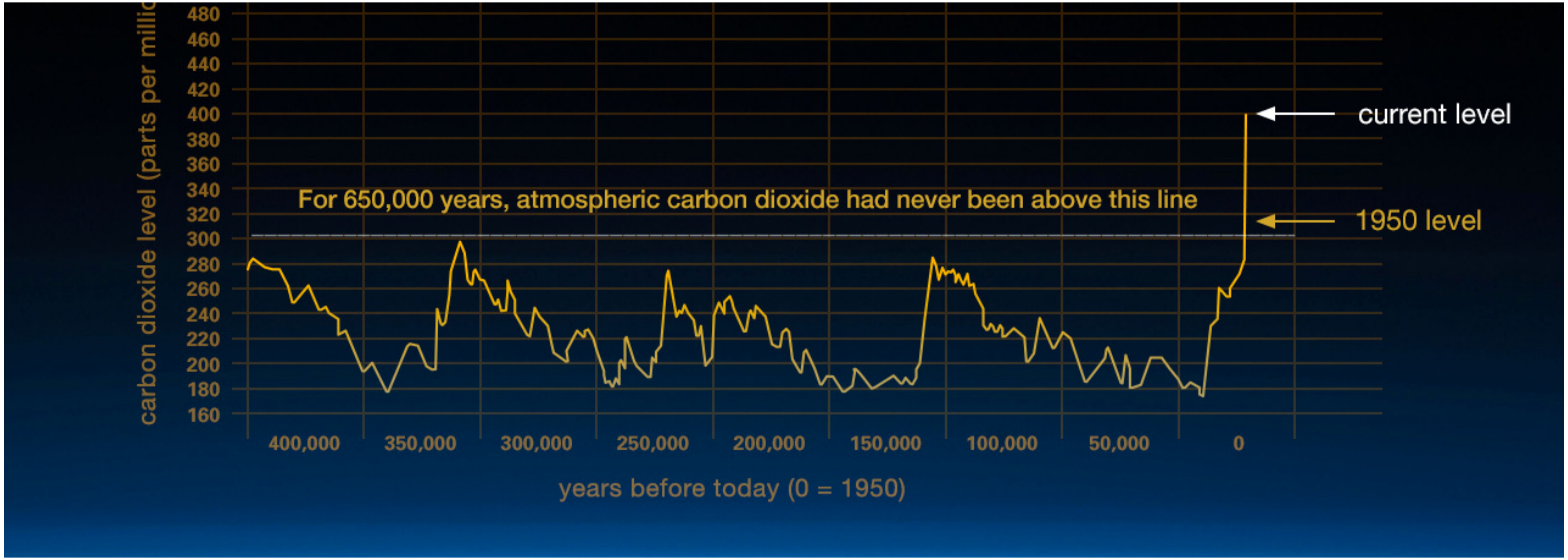
Midterm

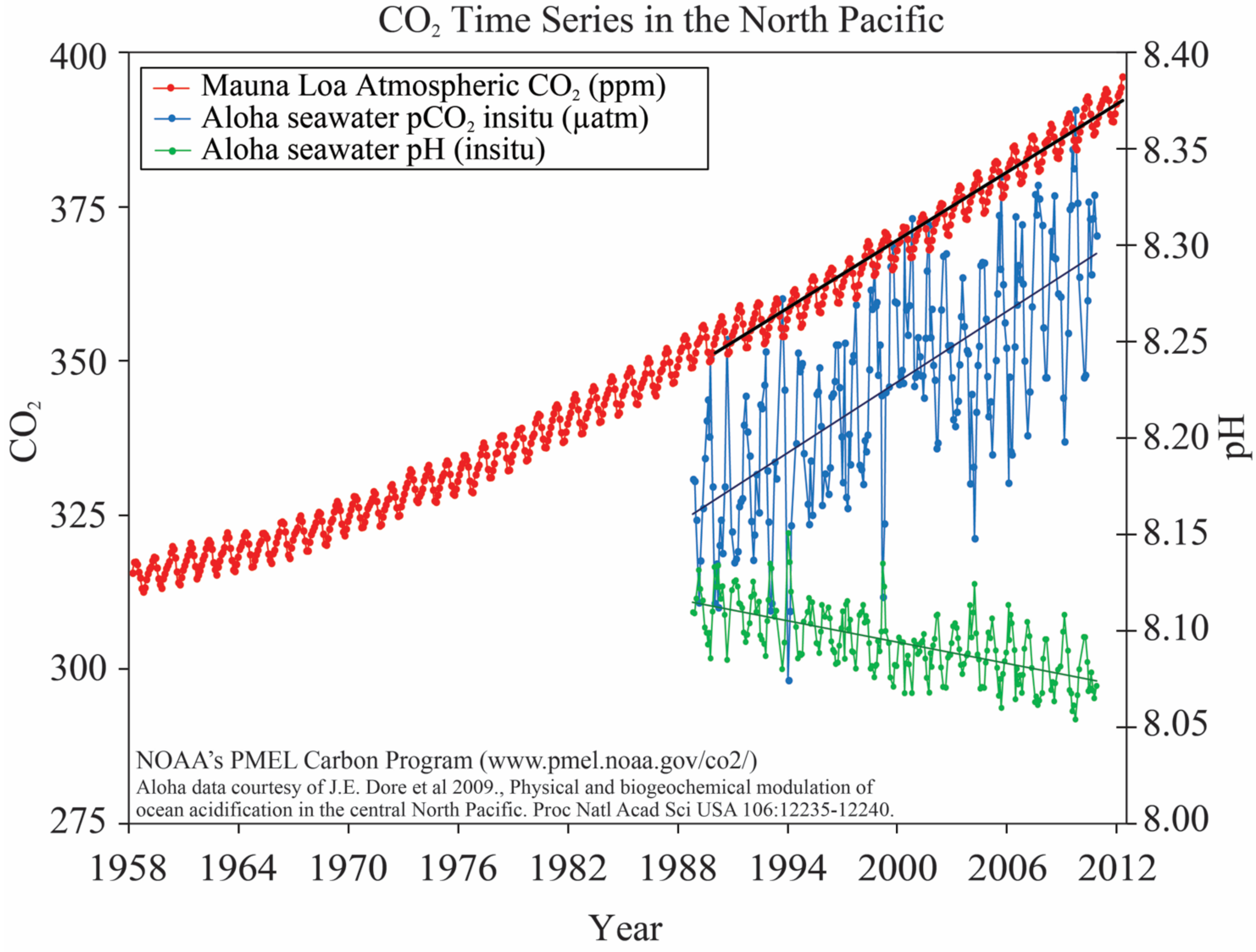
- Nov 15 – in the evening
- Two hours
- Covers all material up through previous lecture
- Maximum 1 page of notes

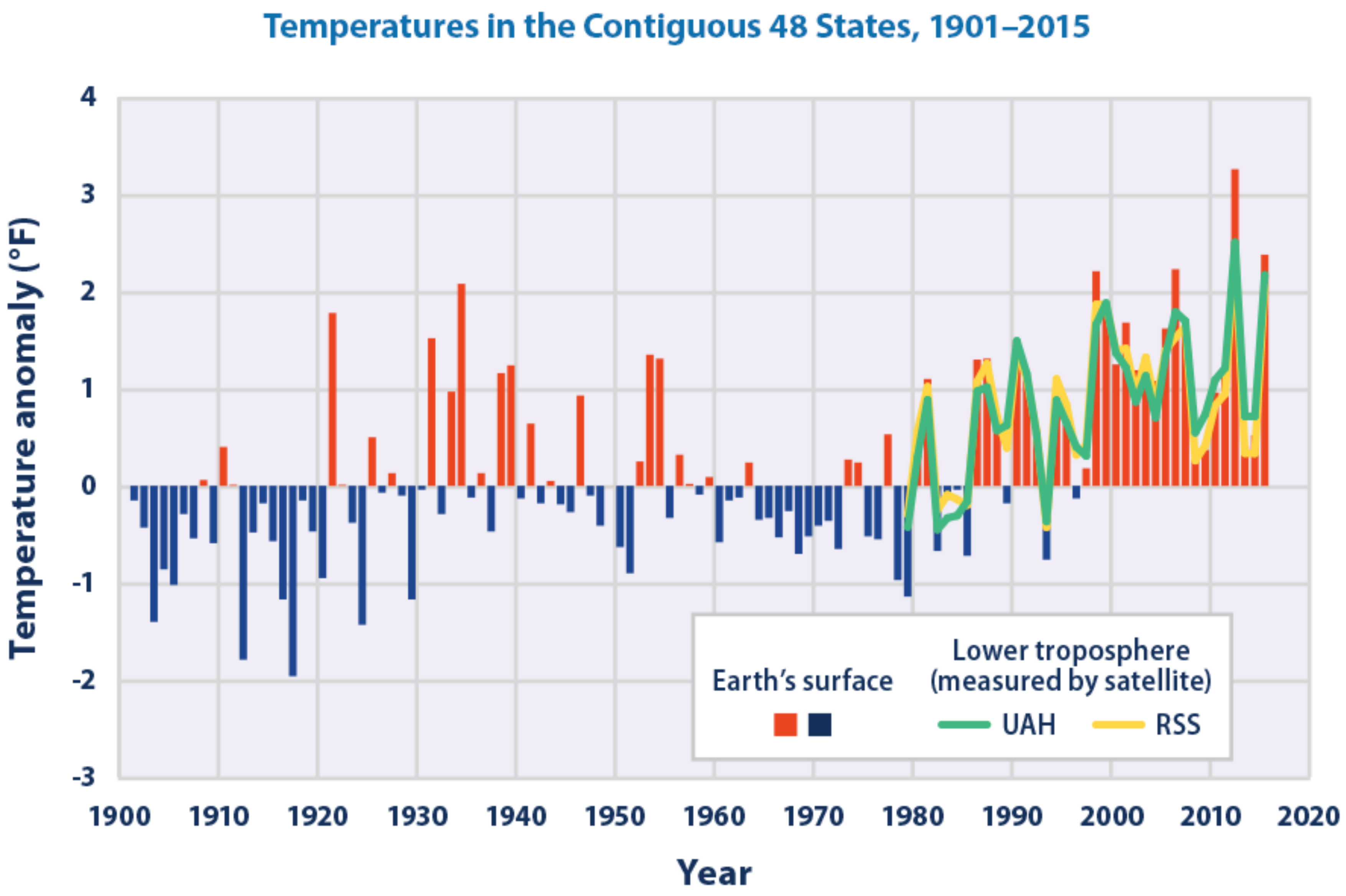
Why Green Electronics?


Atmospheric CO_2 at Mauna Loa Observatory
Scripps Institution of Oceanography
NOAA Earth System Research Laboratory
PARTS PER MILLION
400
380
360
340
320
1960
1970
1980
1990
2000
2010
YEAR
March 2015

Longer-Term View



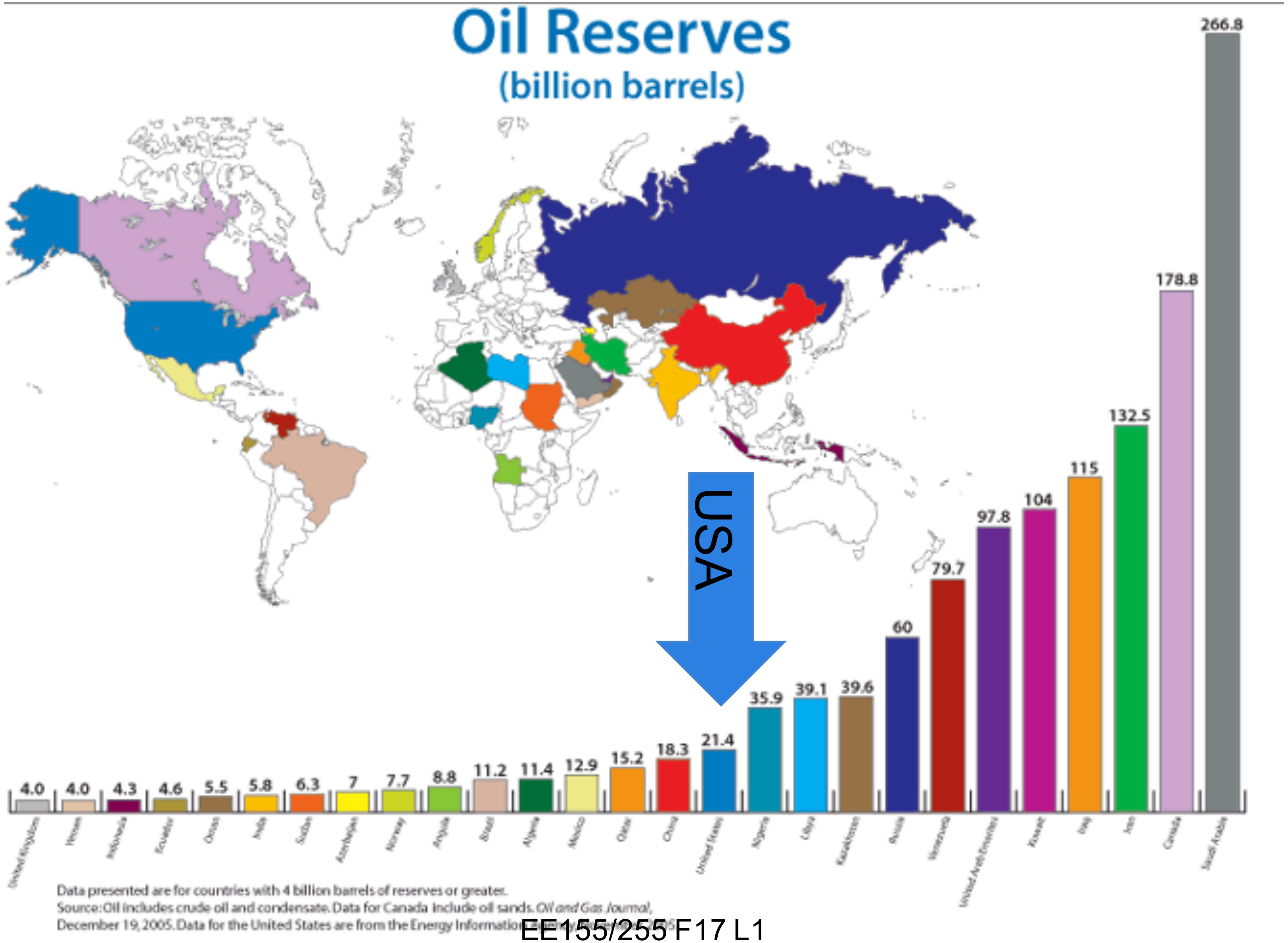

CO2 Time Series in the North Pacific
Mauna Loa Atmospheric CO2 (ppm)
Aloha seawater pCO2 insitu (µatm)
Aloha seawater pH (insitu)
CO2
pH
Year
400
375
350
325
300
275
8.40
8.35
8.30
8.25
8.20
8.15
8.10
8.05
8.00
1958
1964
1970
1976
1982
1988
1994
2000
2006
2012
NOAA's PMEL Carbon Program (www.pmel.noaa.gov/co2/)
Aloha data courtesy of J.E. Dore et al 2009., Physical and biogeochemical modulation of ocean acidification in the central North Pacific. Proc Natl Acad Sci USA 106:12235-12240.



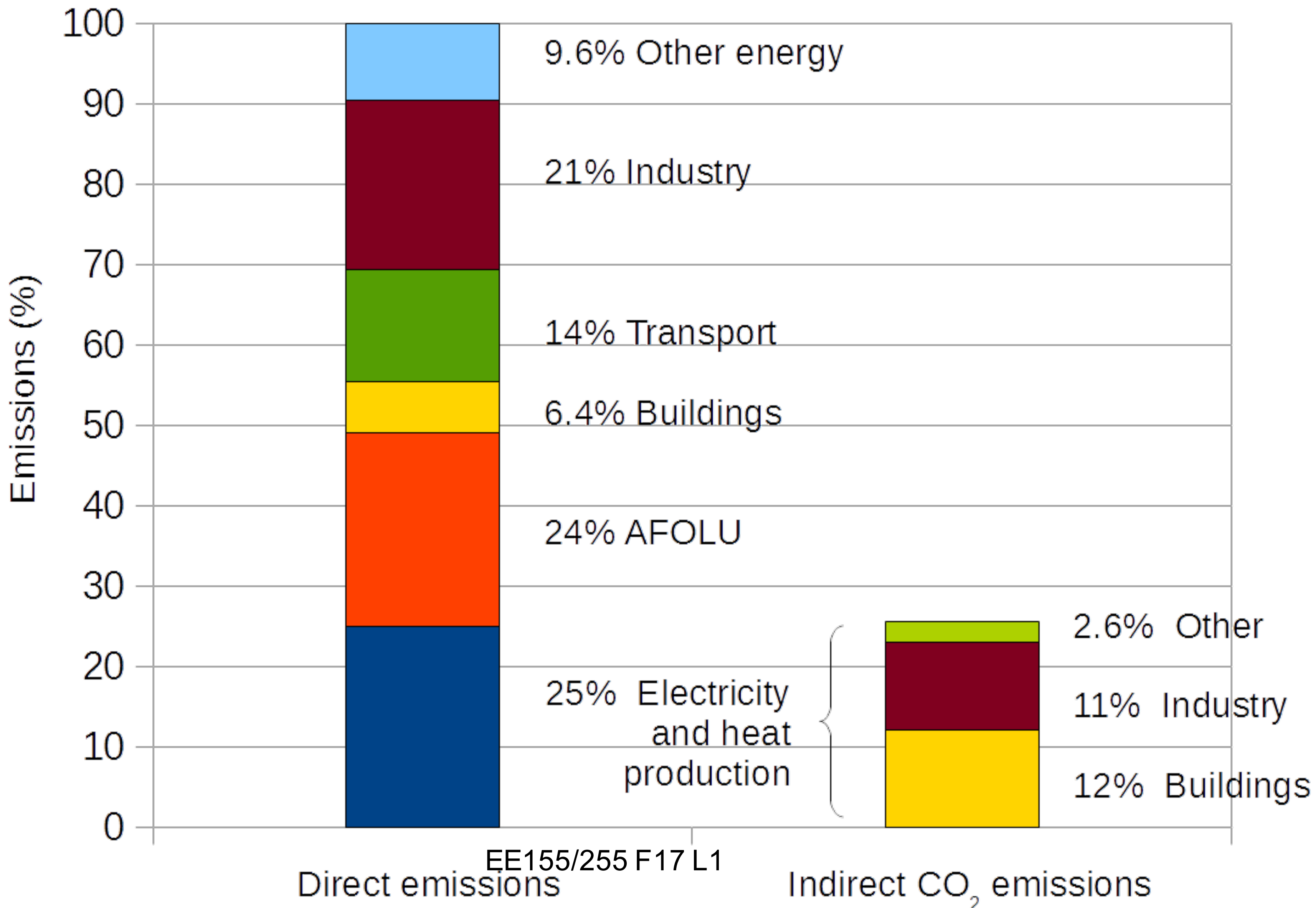
Data source: NOAA (National Oceanic and Atmospheric Administration). 2016. National Centers for Environmental Information. Accessed February 2016. www.ncei.noaa.gov.

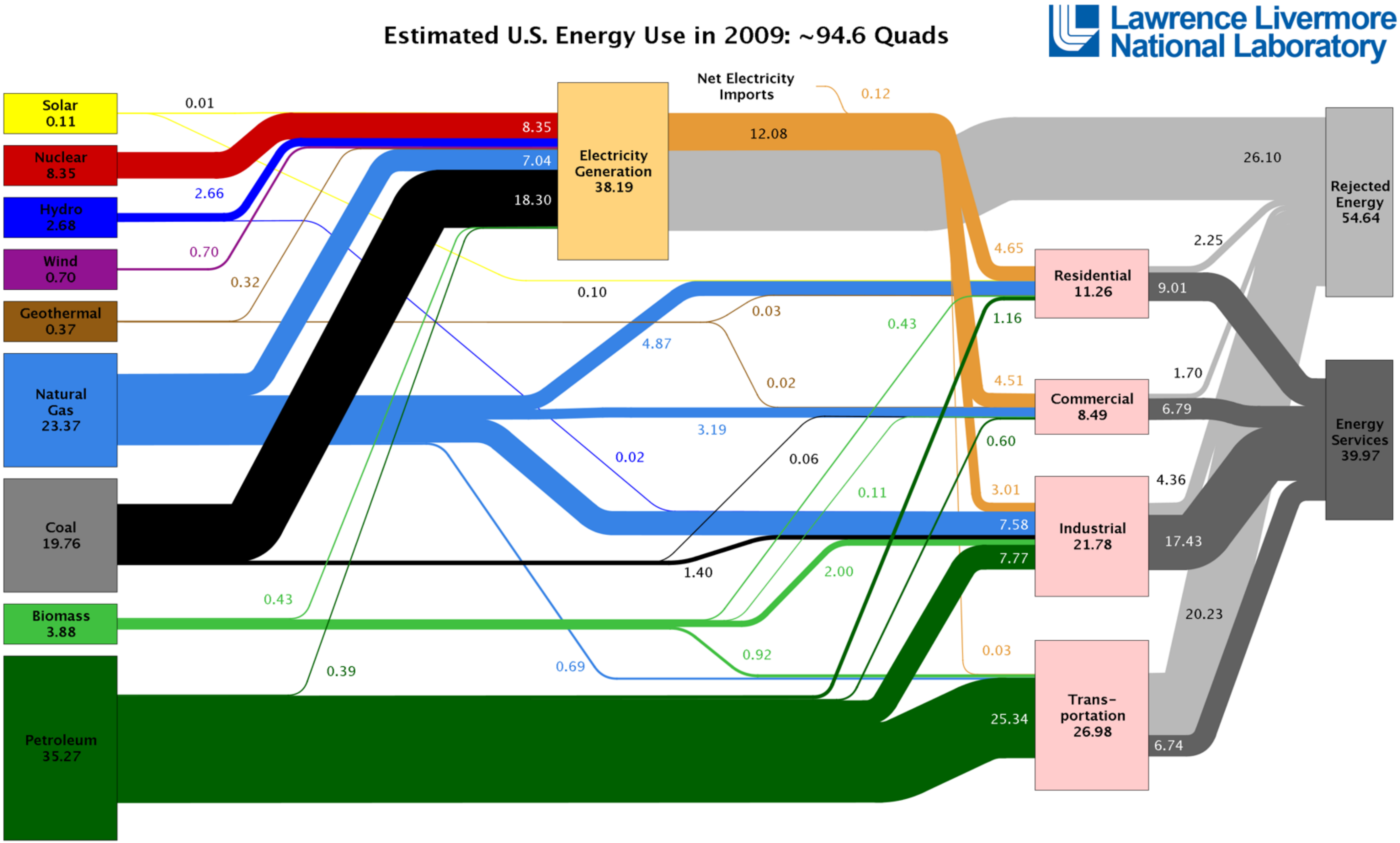
For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators.

2. Finite Supply of Fossil Fuels



Global Emissions by source

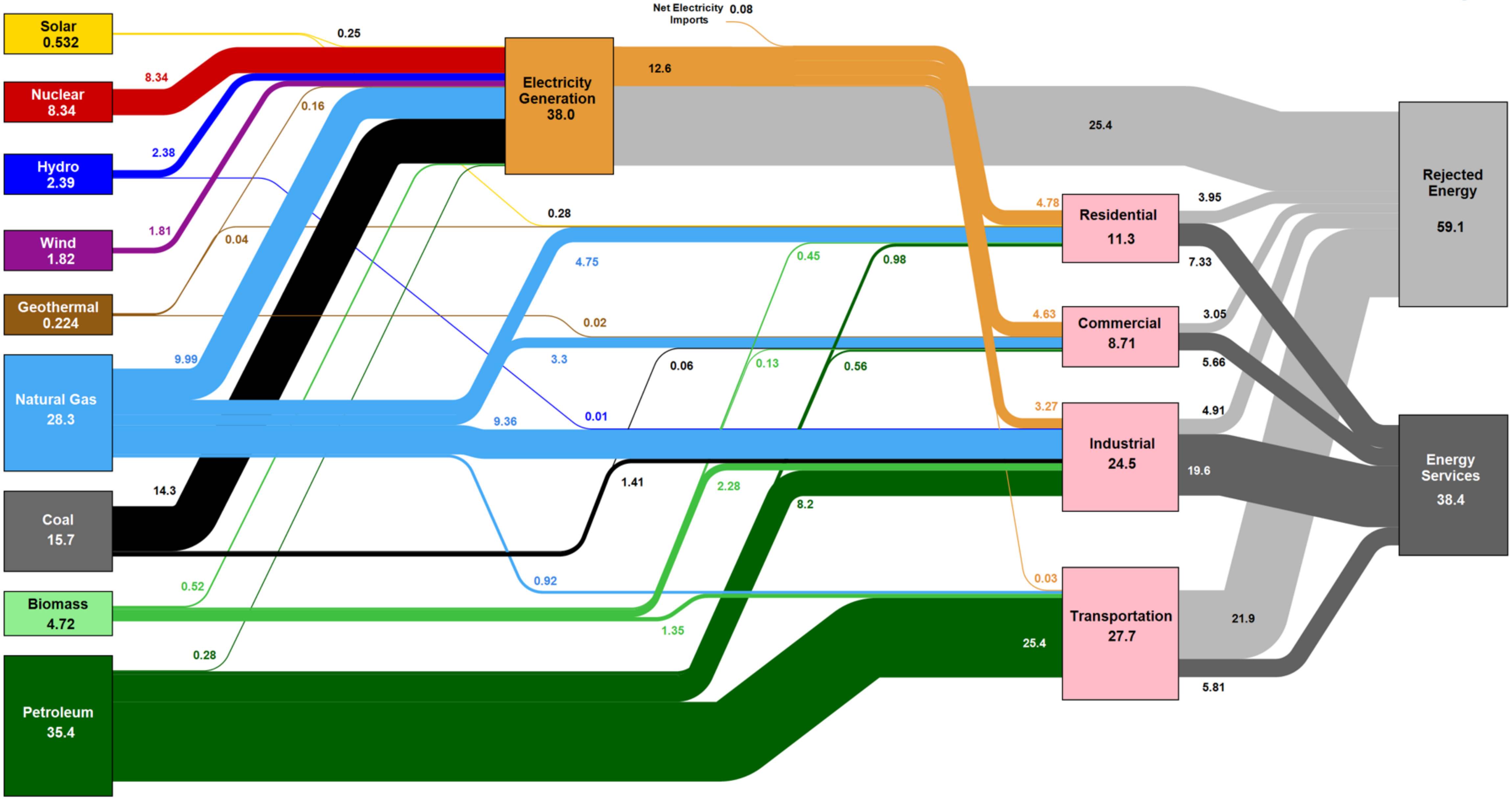




Source: LLNL 2010. Data is based on DOE/EIA-0384(2009), August 2010. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for non-thermal resources (i.e., hydro, wind and solar) in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Estimated U.S. Energy Consumption in 2015: 97.5 Quads

Lawrence Livermore National Laboratory

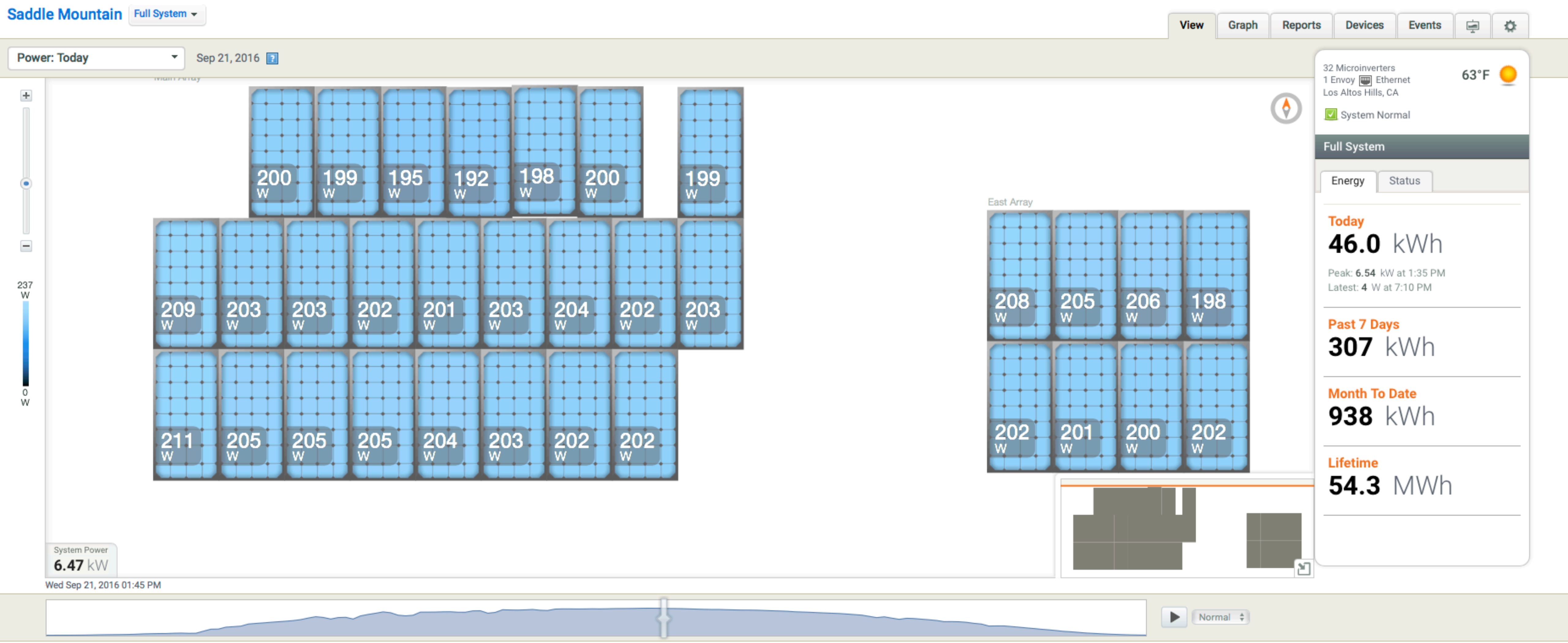


Source: LLNL March, 2016. Data is based on DOE/EIA MER (2015). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent Rounding. LLNL-MI-410527

Green Electronics is Part of the Solution

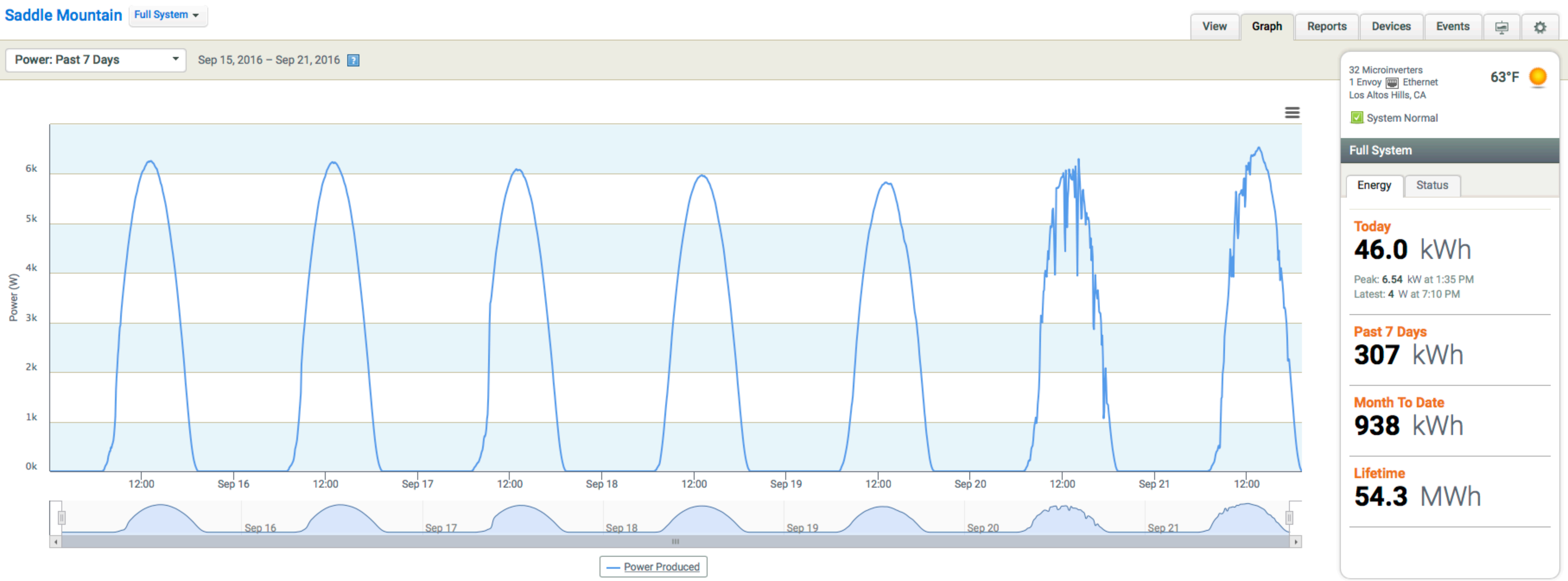
What is Green Electronics?


Sunny Boy

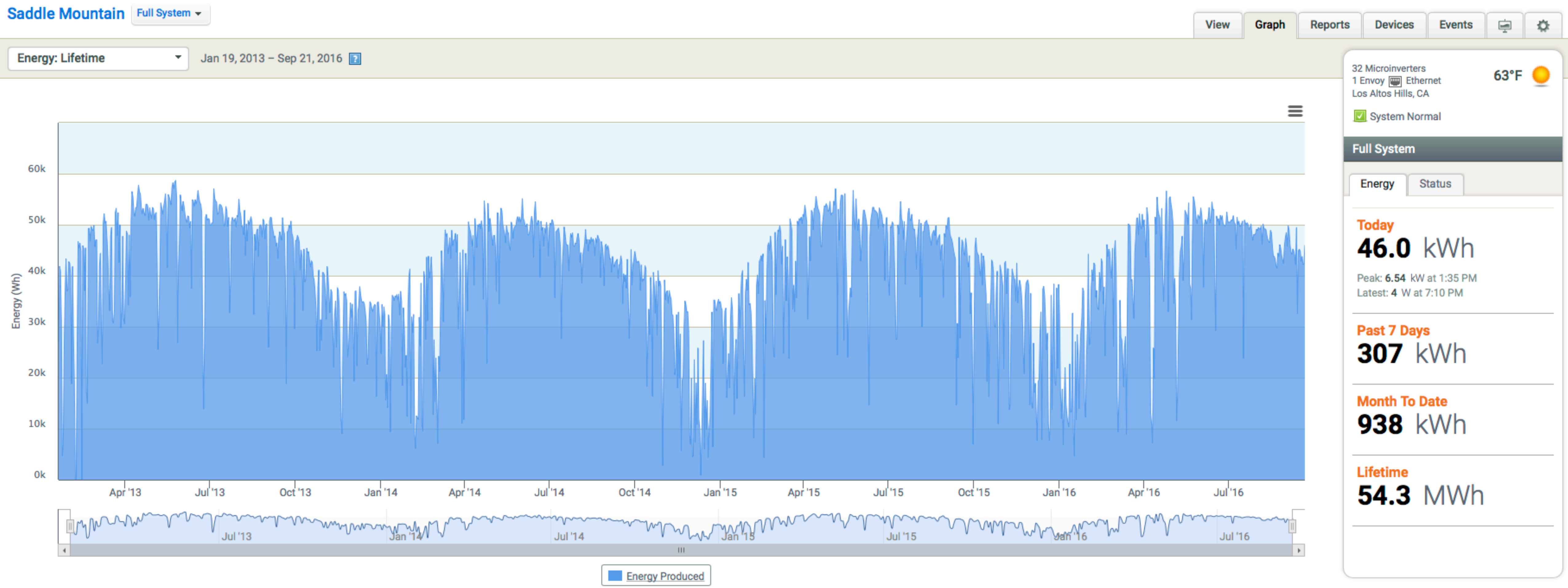


Saddle Mountain
Full System
View
Graph
Reports
Devices
Events
Power: Today
Sep 21, 2016
32 Microinverters
1 Envoy Ethernet
Los Altos Hills, CA
63°F
System Normal
Full System
Energy
Status
Today
46.0 kWh
Peak: 6.54 kW at 1:35 PM
Latest: 4 W at 7:10 PM
Past 7 Days
307 kWh
Month To Date
938 kWh
Lifetime
54.3 MWh
East Array
200 W
199 W
195 W
192 W
198 W
200 W
199 W
209 W
203 W
203 W
202 W
201 W
203 W
204 W
202 W
203 W
211 W
205 W
205 W
205 W
204 W
203 W
202 W
202 W
208 W
205 W
206 W
198 W
202 W
201 W
200 W
202 W
237 W
0 W
System Power
6.47 kW
Wed Sep 21, 2016 01:45 PM
Normal

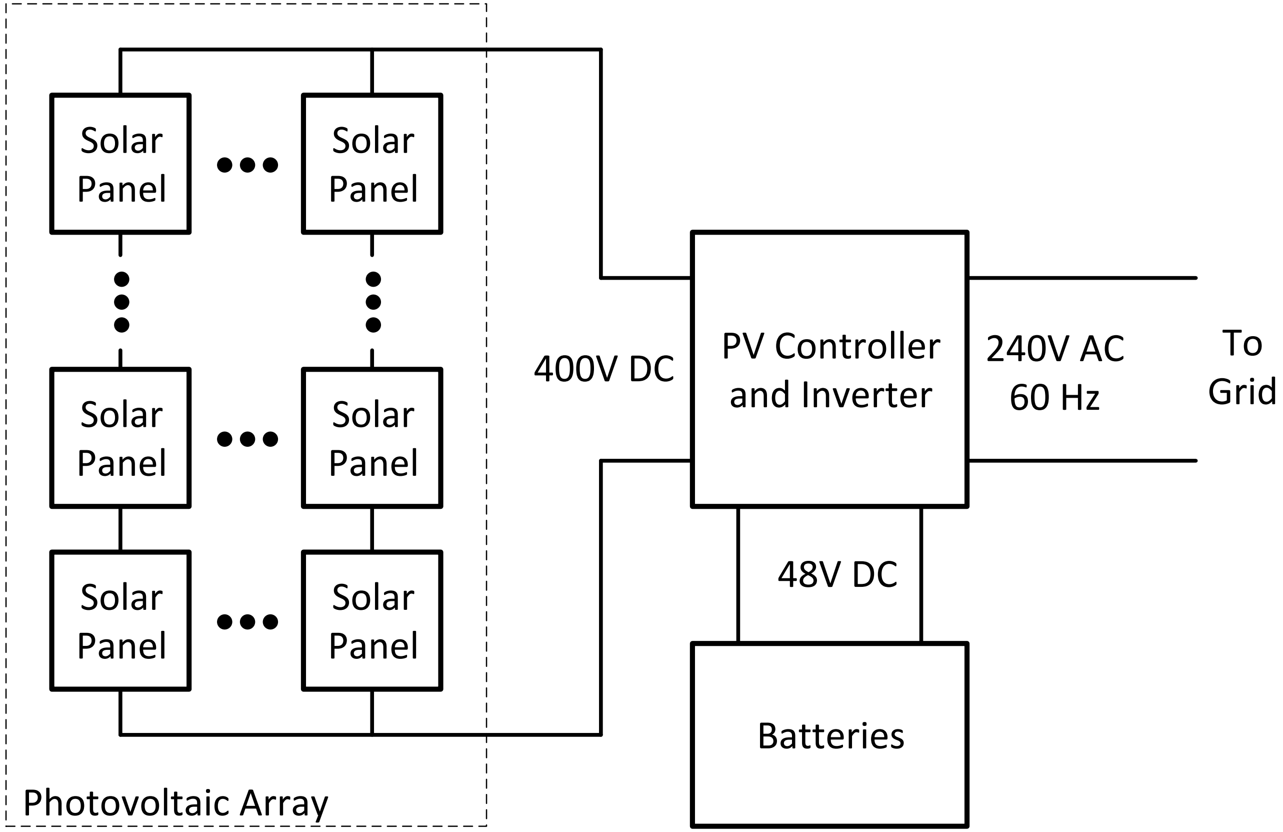
Variability of Solar



Variability of Solar

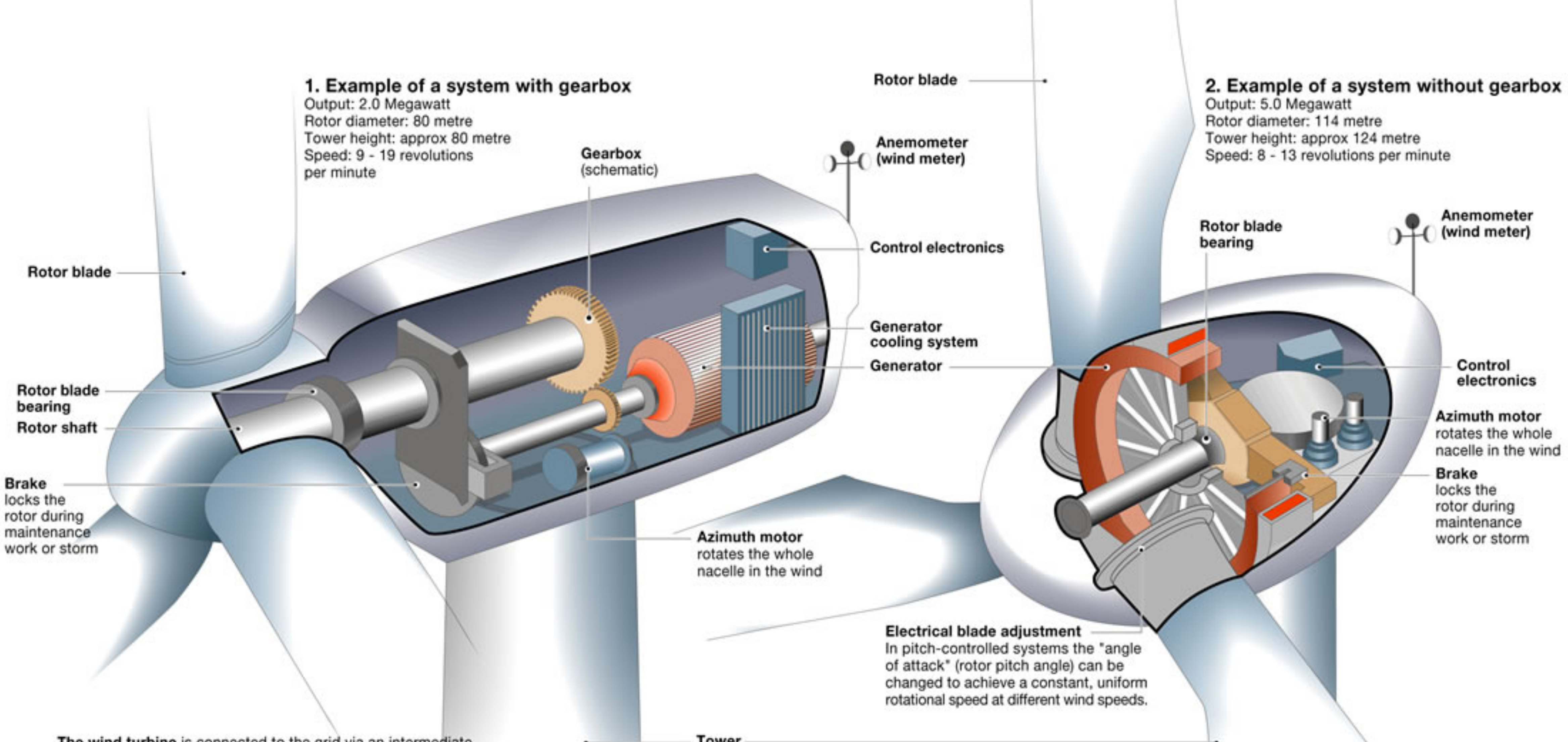


Photovoltaic System



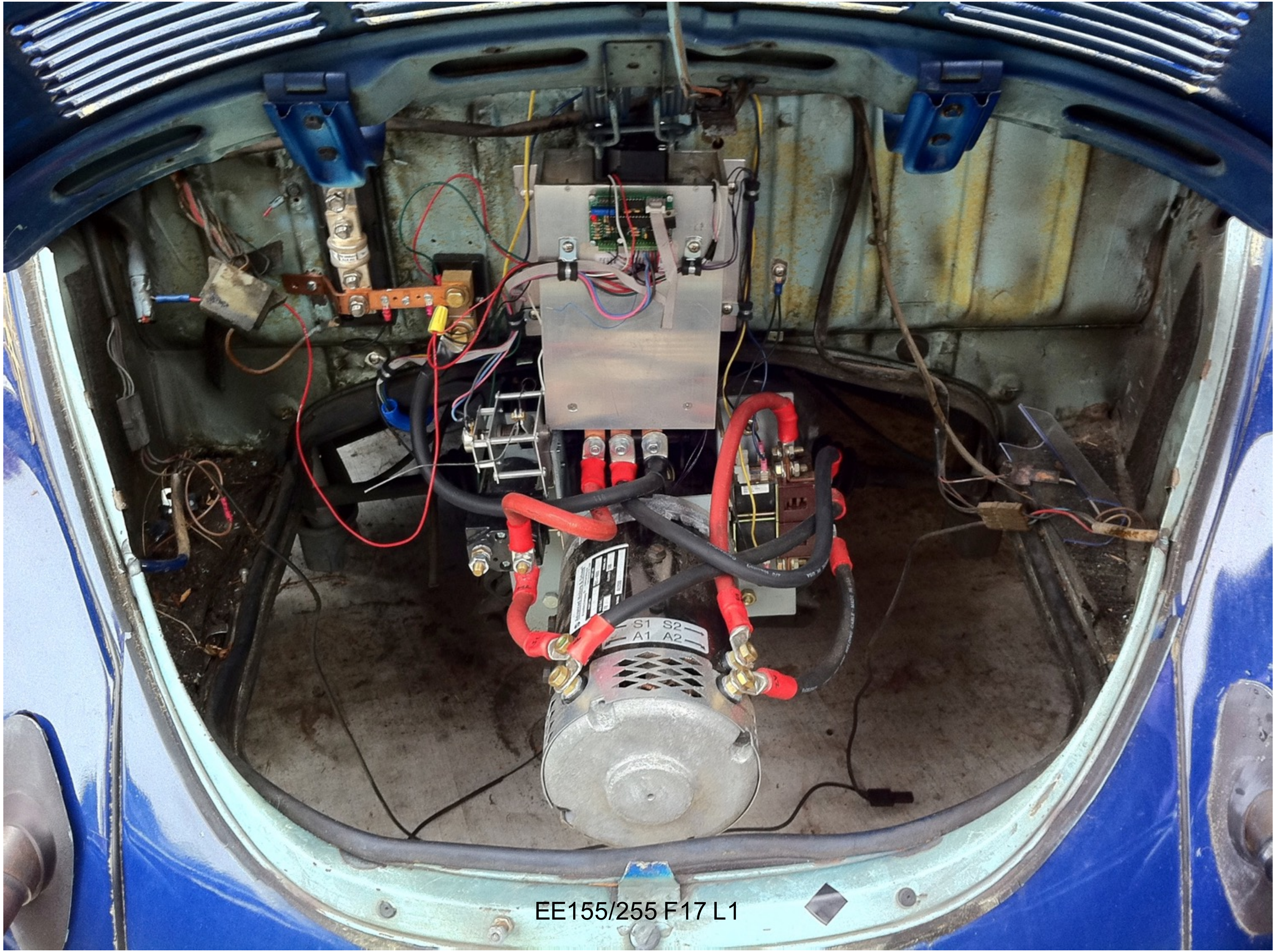
Wind energy

Two different design principles have established themselves for wind turbines: Systems with gearbox (1.) increase the low speed of the generator to a favourable speed for the generator.

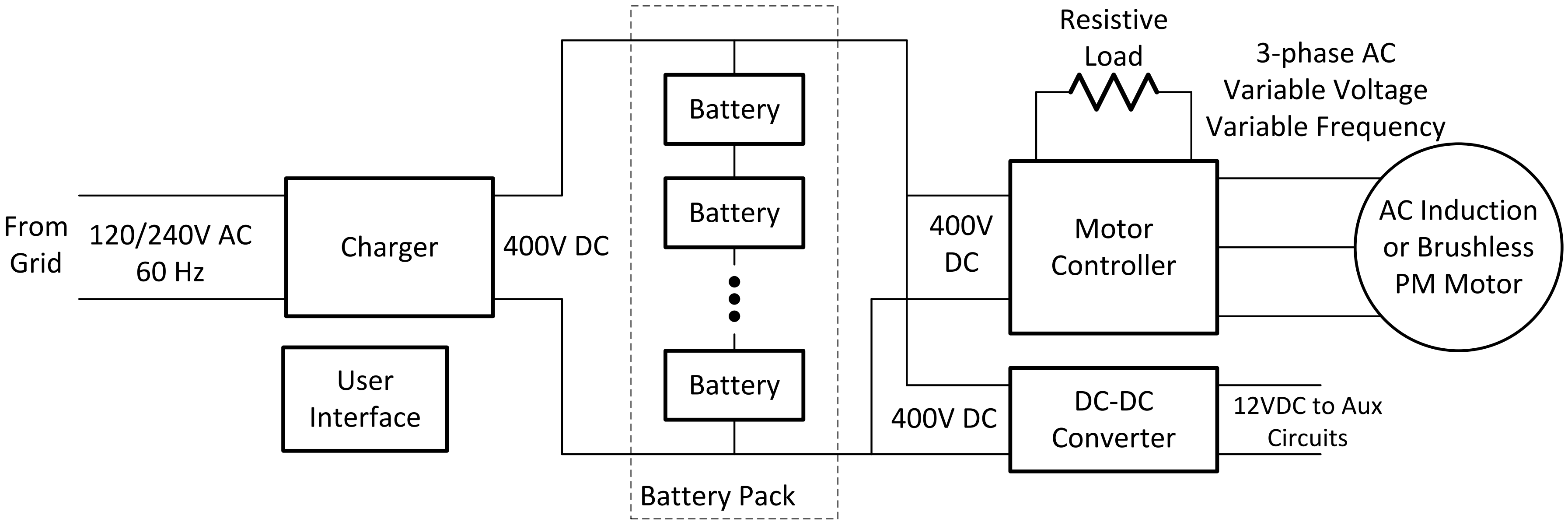


The wind turbine is connected to the grid via an intermediate direct current circuit. The alternating current generated by the generator is first converted into direct current and is then converted back into alternating current with the correct frequency and voltage. This enables variable-speed operation of the wind turbine and the mechanical stresses are minimised.

Agentur für Erneuerbare Energien

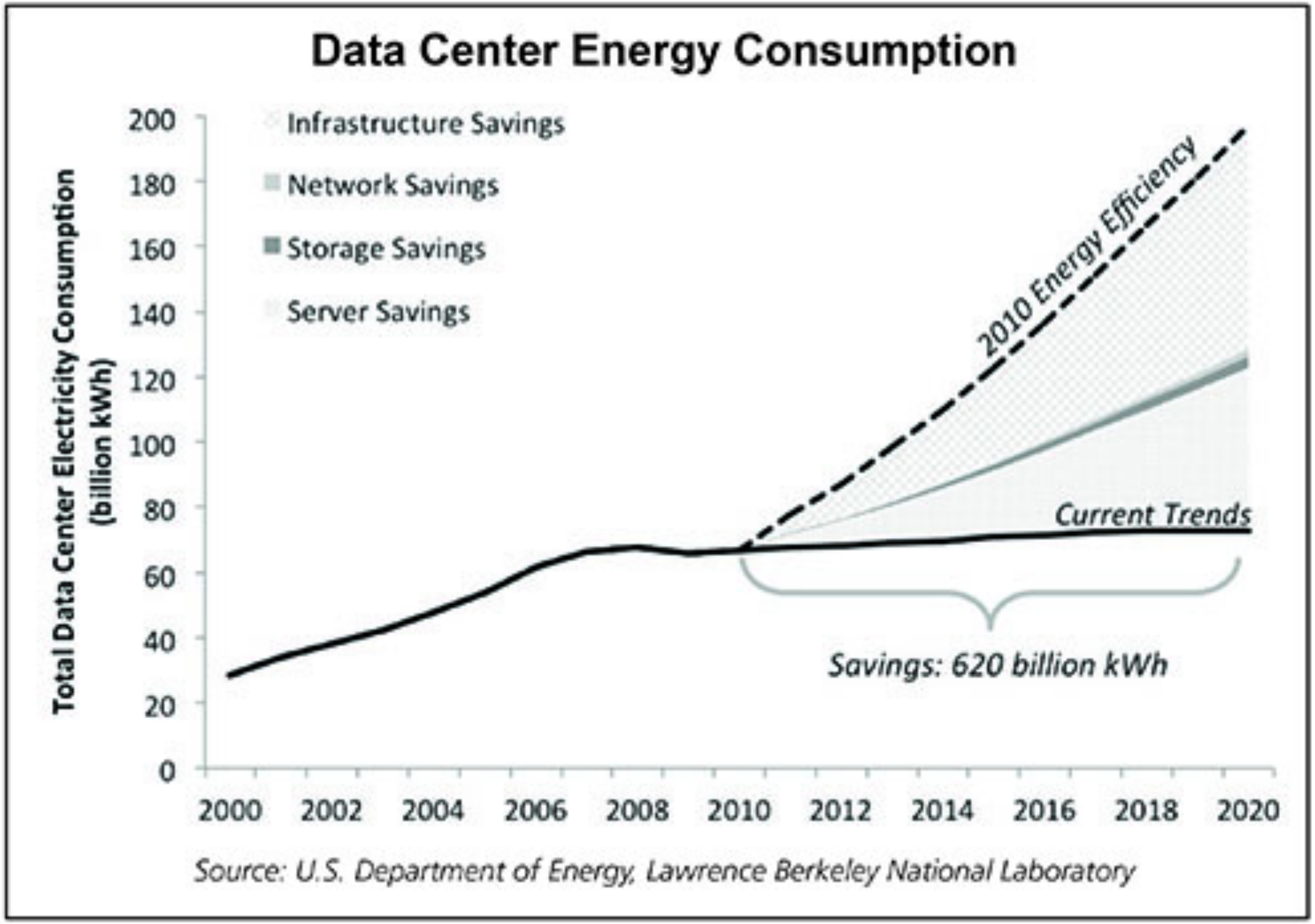

S1 S2
A1 A2

Electric Car



Less Obvious

Green Electronics Success Story



A great vehicle to teach Engineering

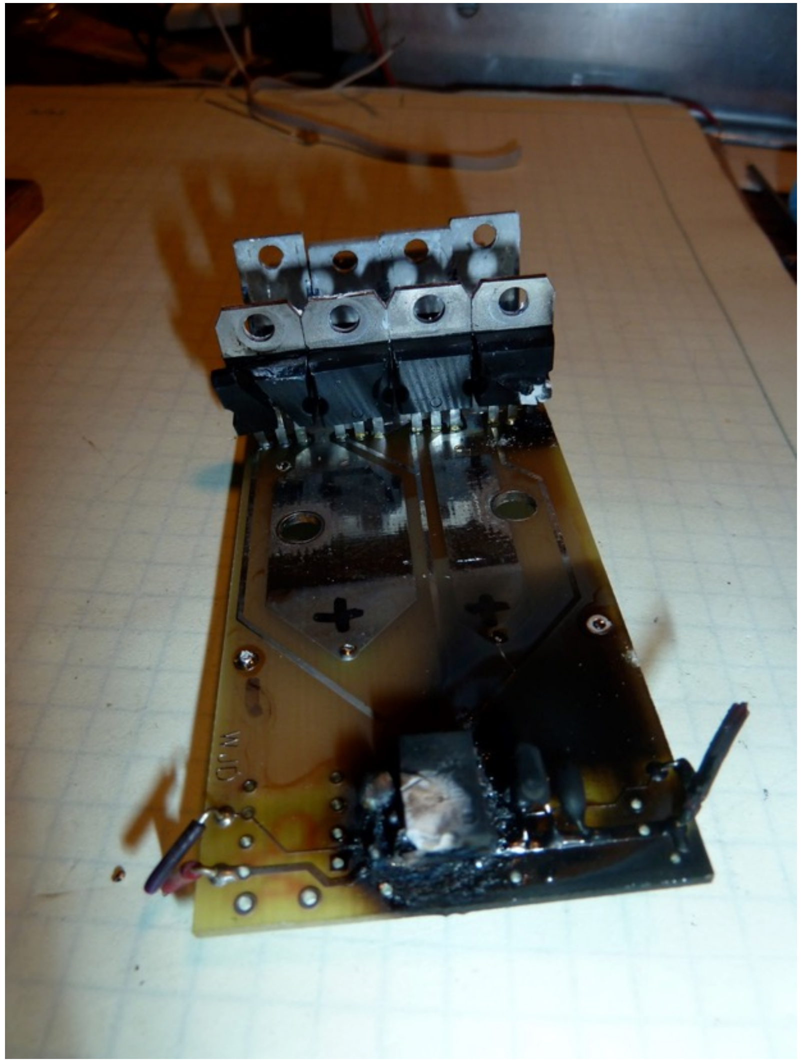
Interesting examples to teach methods

- Analyze – of a circuit or a system
- Synthesize – a circuit, a system, software
- Model – a physical thing
- Simulate – your system or circuit
- Optimize – efficiency, performance, cost, etc…

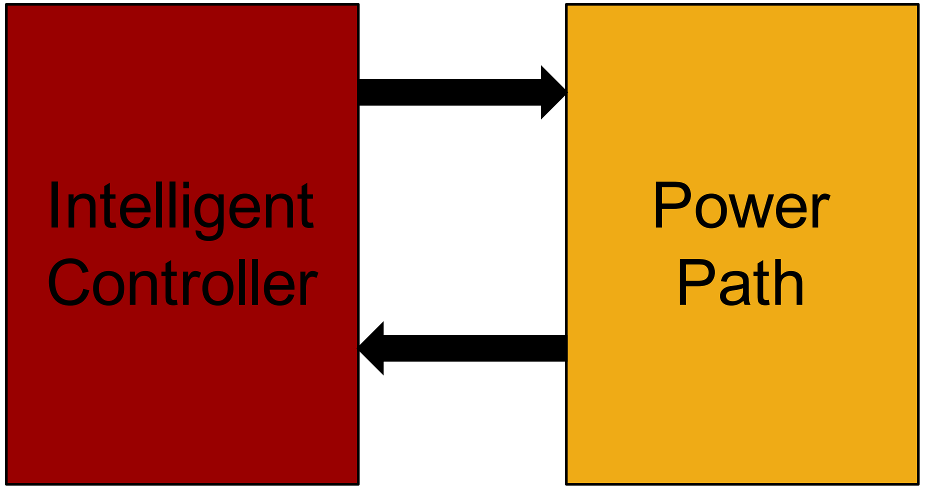
Interrelating Topics

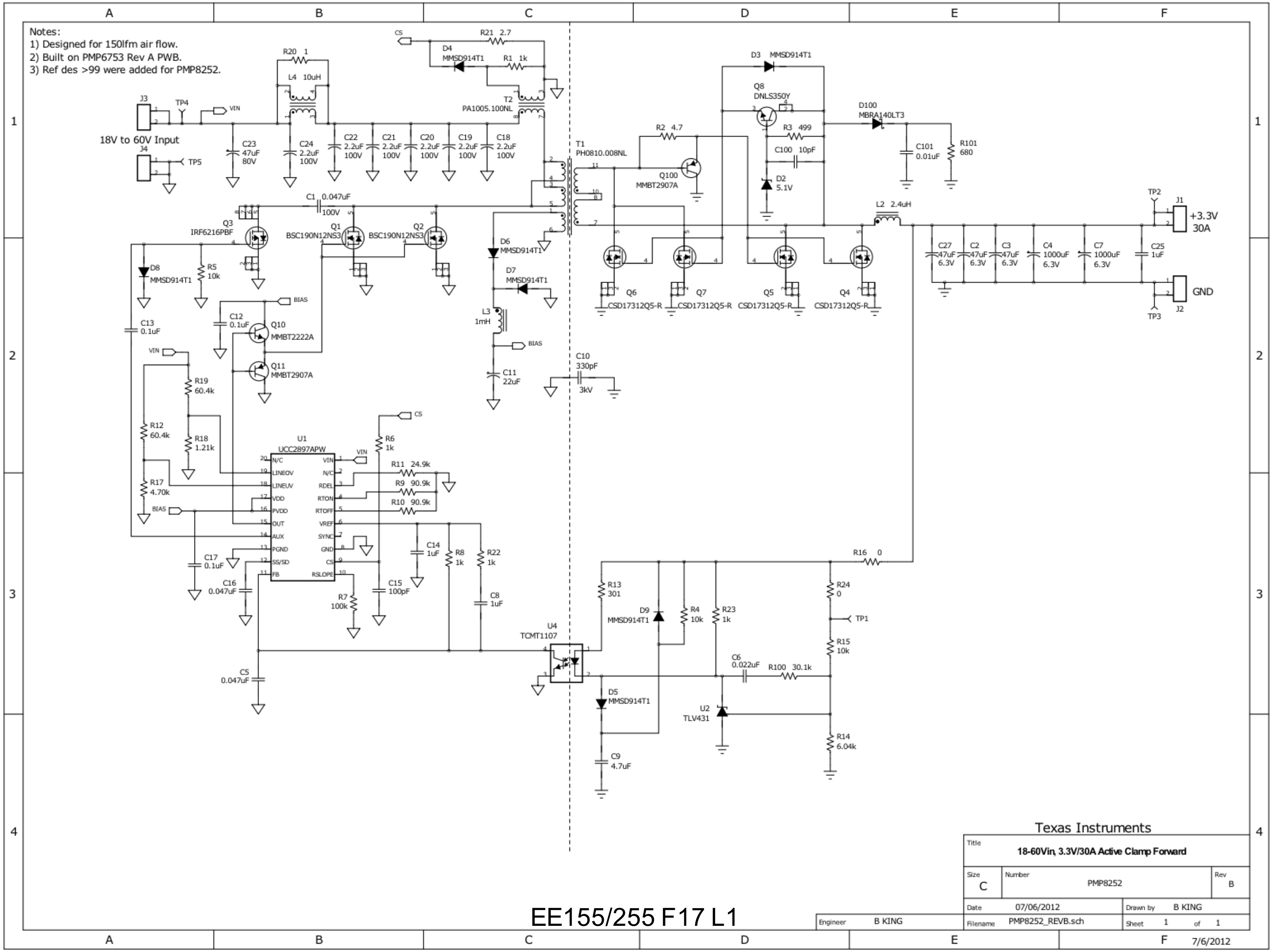
- Electronics
- Electro-mechanical system
- Thermal effects
- Magnetic components
- Power Semiconductors
- …

Bugs have consequences

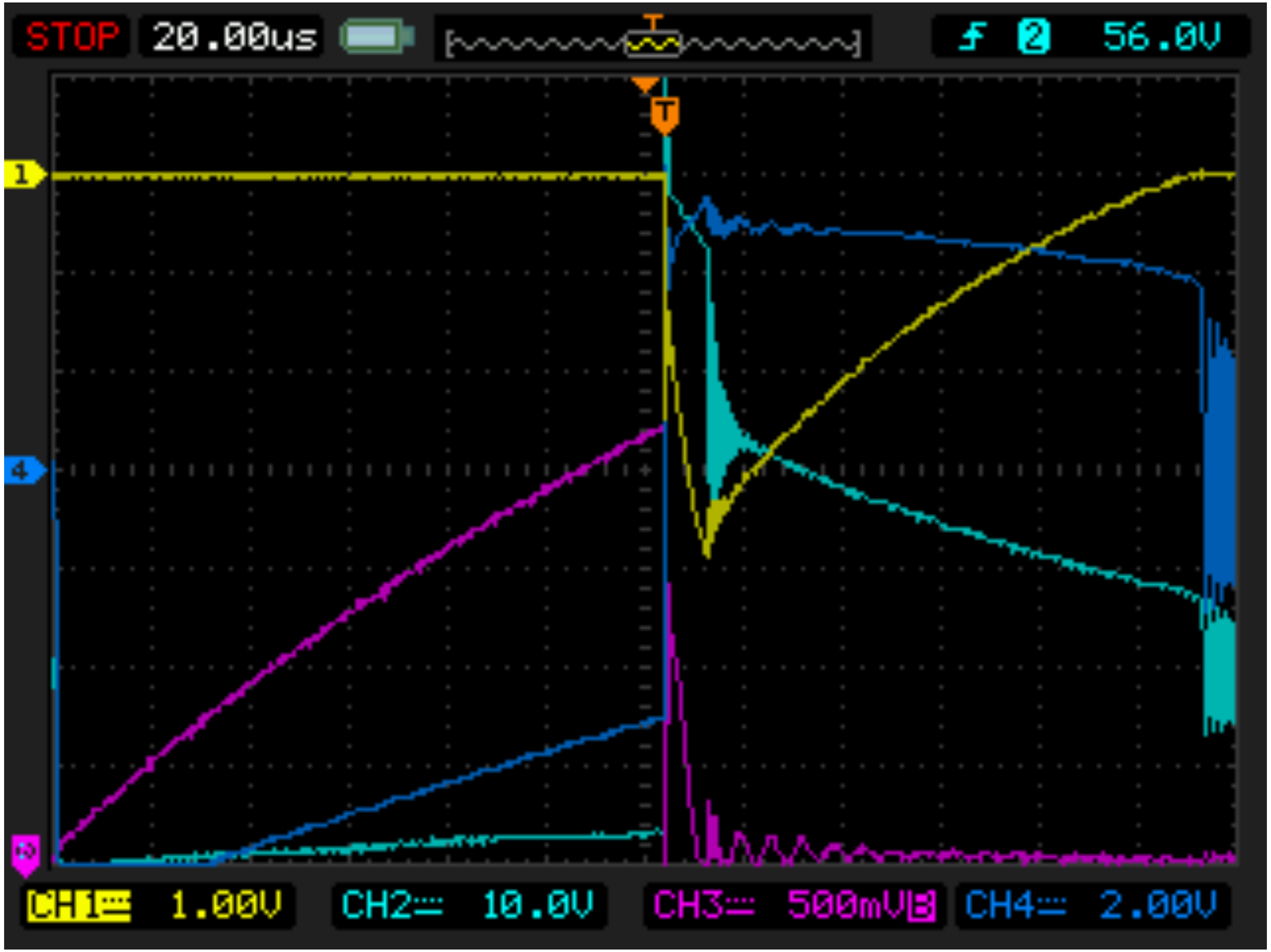


Power Electronics + Intelligent Control




Notes:
1) Designed for 150lfm air flow.
2) Built on PMP6753 Rev A PWB.
3) Ref des >99 were added for PMP8252.
18V to 60V Input
+3.3V 30A
GND
Texas Instruments
Title
18-60Vin, 3.3V/30A Active Clamp Forward
Size C
Number PMP8252
Rev B
Date 07/06/2012
Drawn by B KING
Engineer B KING
Filename PMP8252_REVB.sch
Sheet 1 of 1
7/6/2012

Example Waveforms



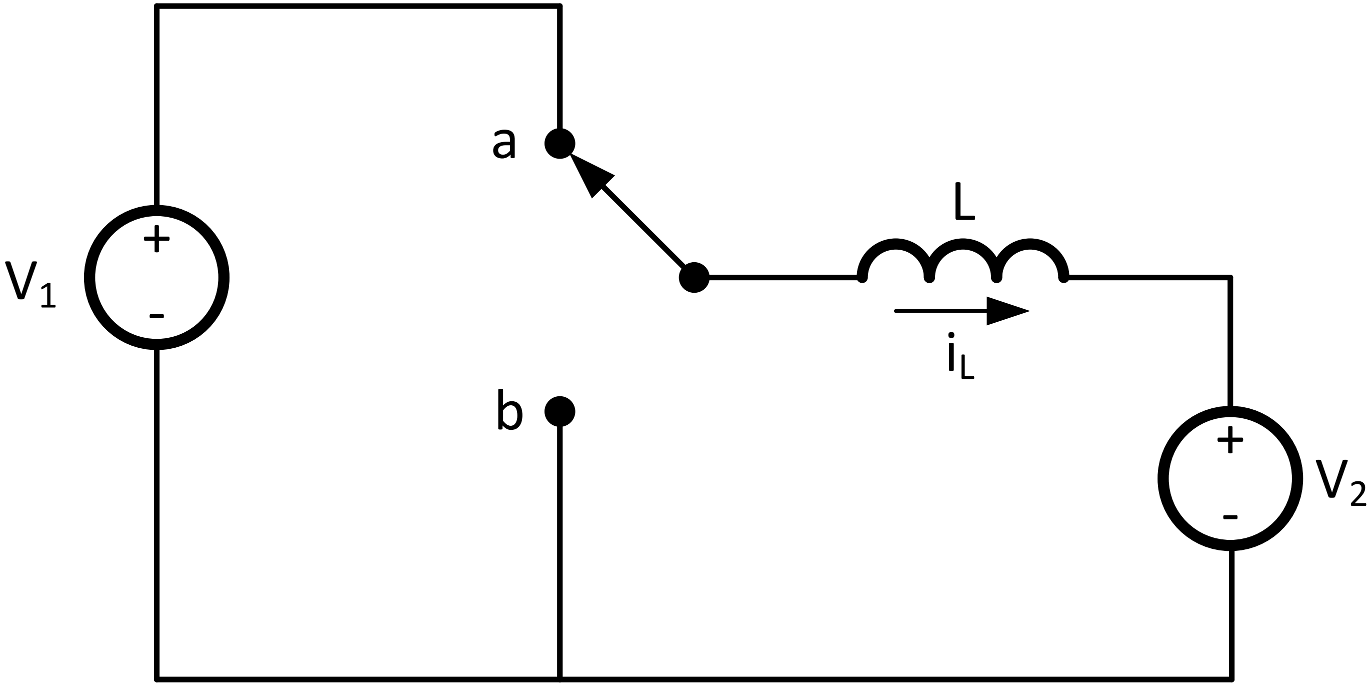
Recap

Advice

End of Lecture 1

Periodic Steady State Analysis

Buck Converter



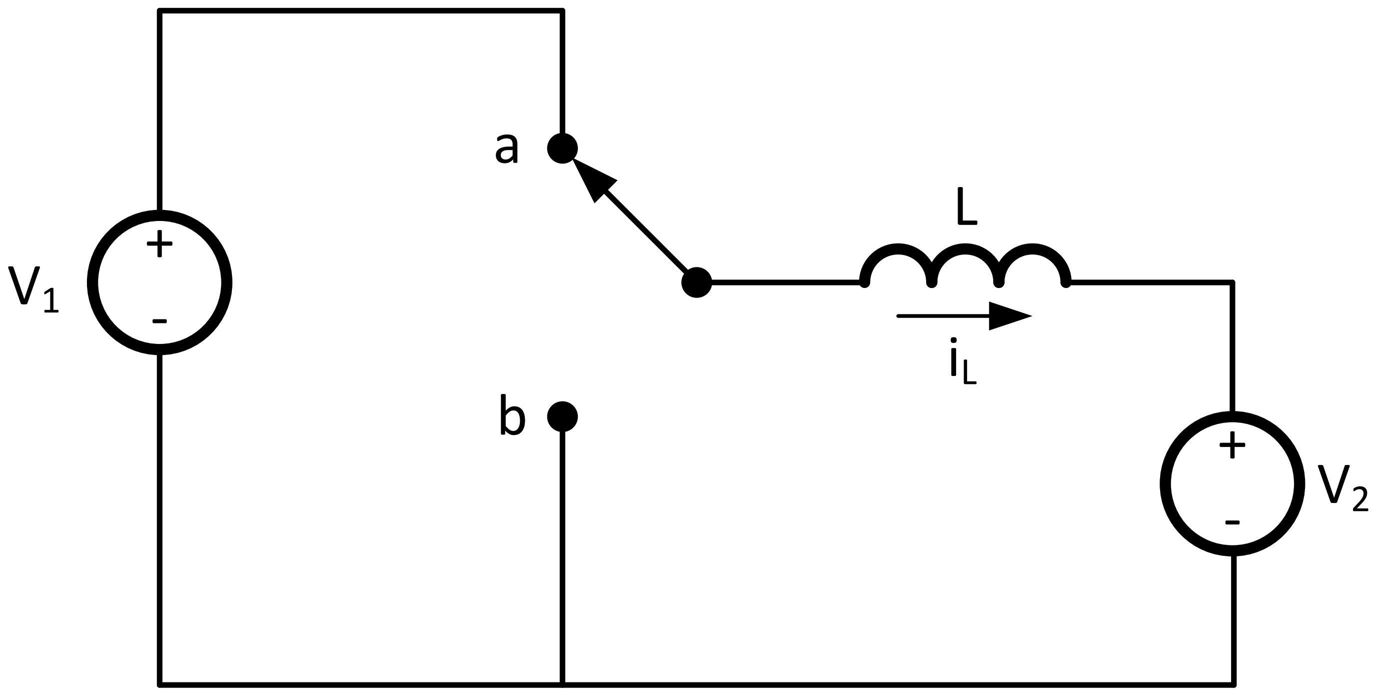
Periodic Steady State

Switch is periodic with cycle time t_{cy}

Separate behavior

Over one cycle of switch

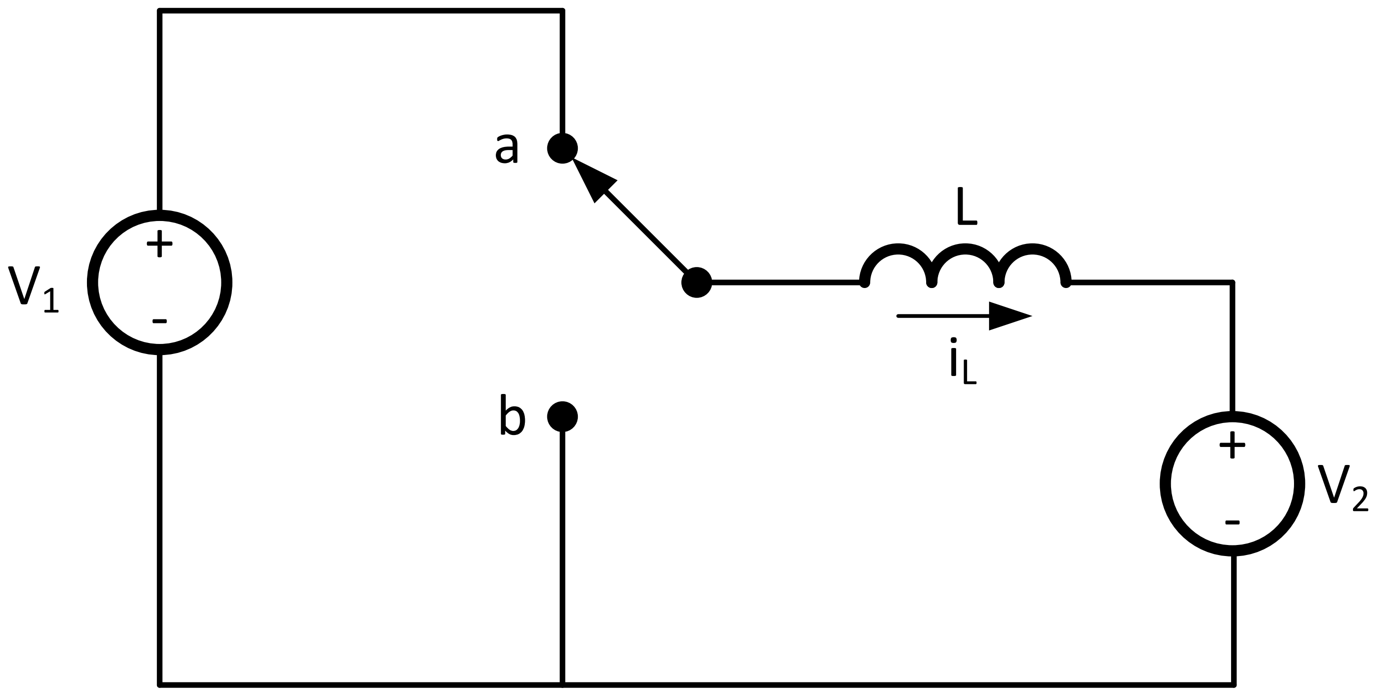
At frequencies much lower than f_{cy}



Periodic Steady State

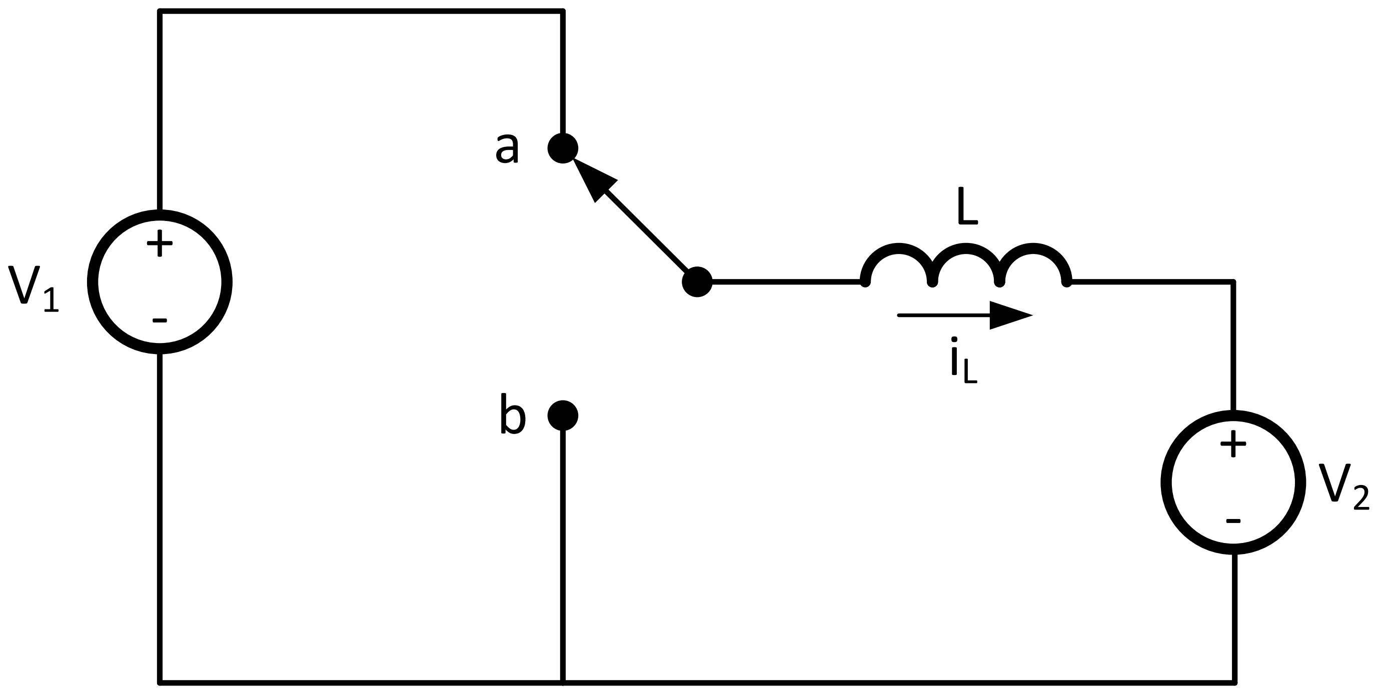
Time is divided into cycles with period t_{cy}

State variables are the same at the beginning and end of each cycle



Periodic Steady State

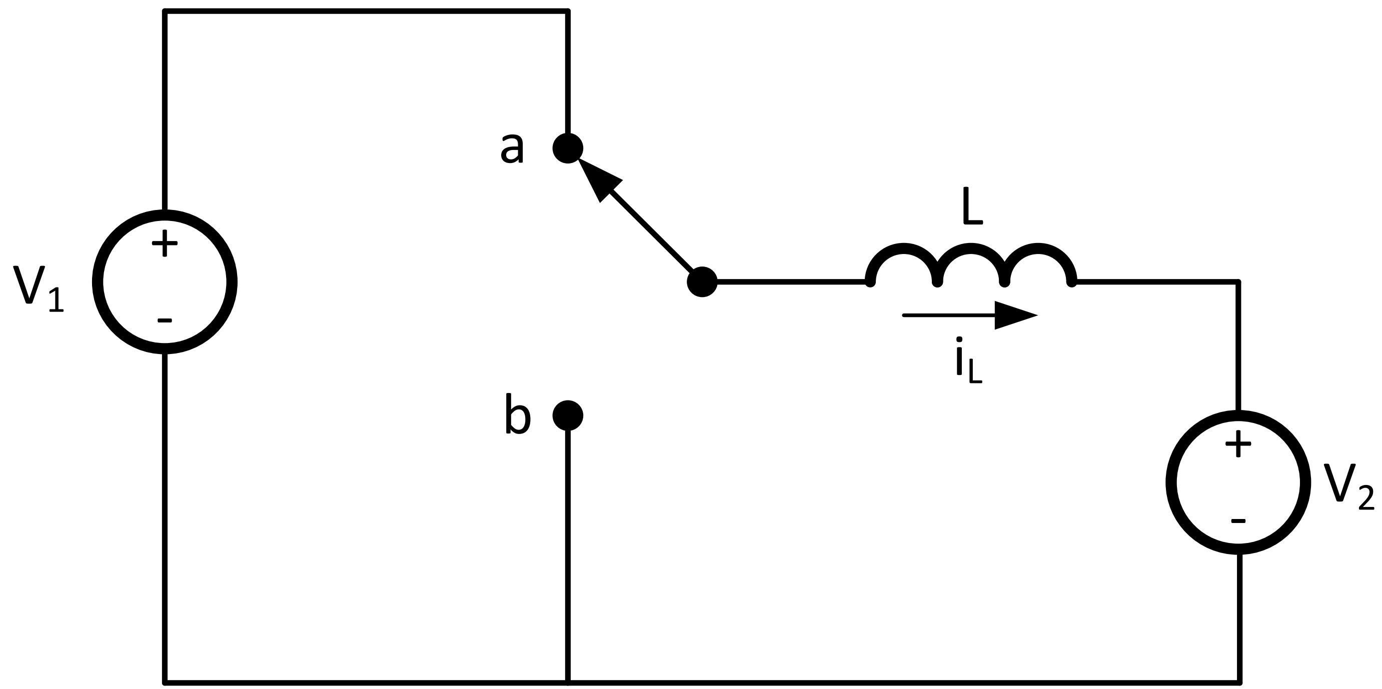
Each cycle:
switch in position ***a*** for t_a, ***b*** for $t_b = t_{cy} - t_a$



Position a

$$V_L = V_1 - V_2$$

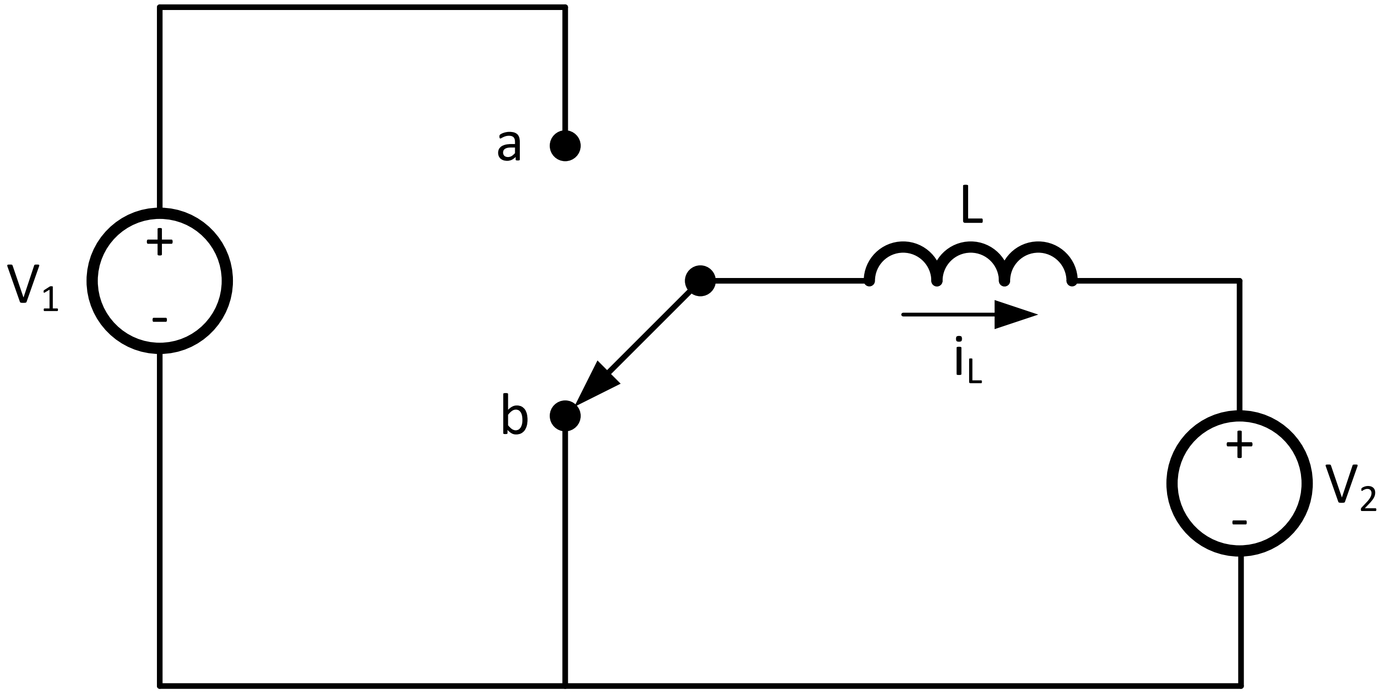
$$\Delta I_a = \frac{t_a V_L}{L} = \frac{t_a\left(V_1 - V_2\right)}{L}$$



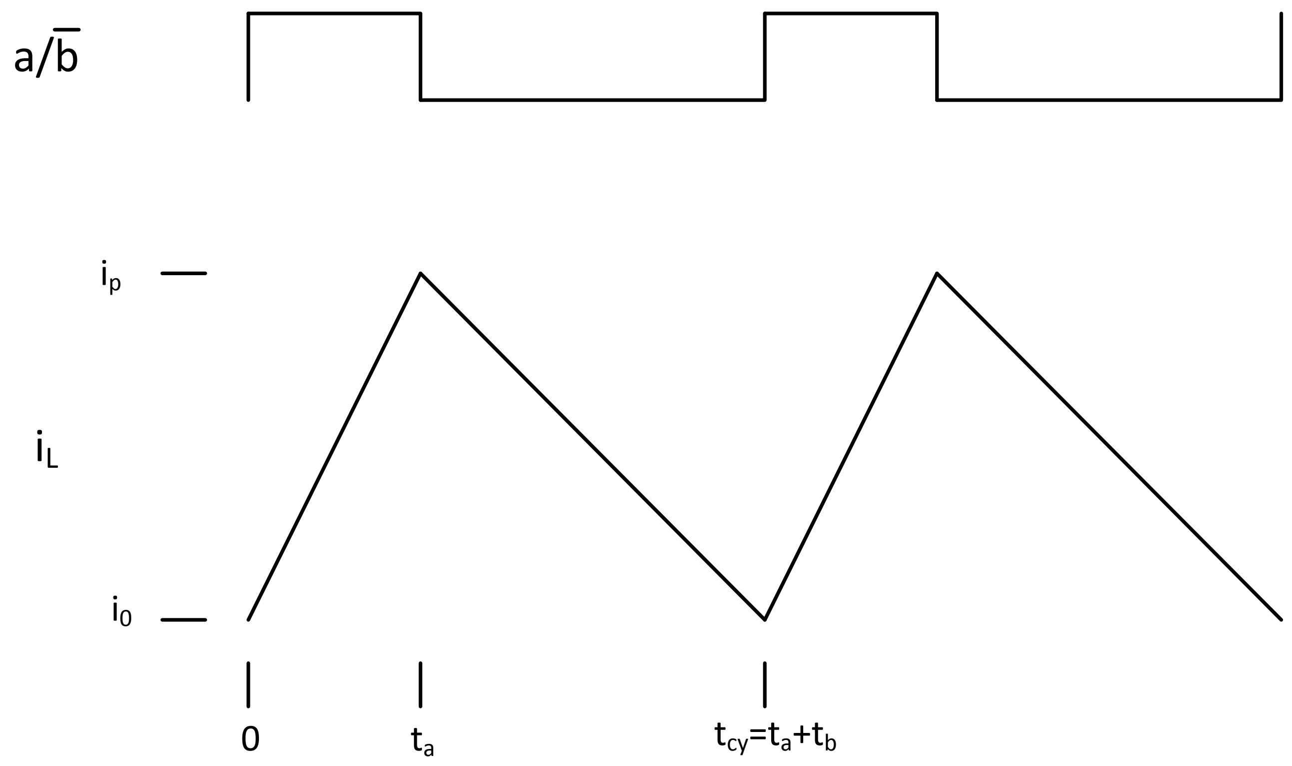
Position b

$$V_L = -V_2$$

$$\Delta I_b = \frac{-t_b V_2}{L}$$

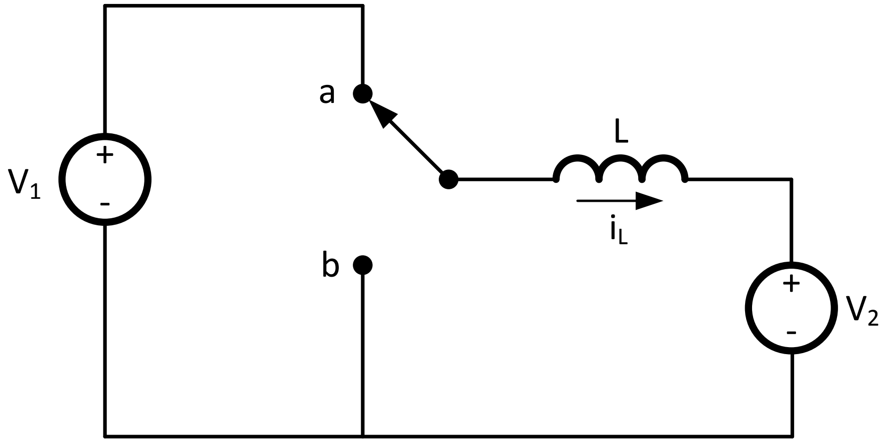


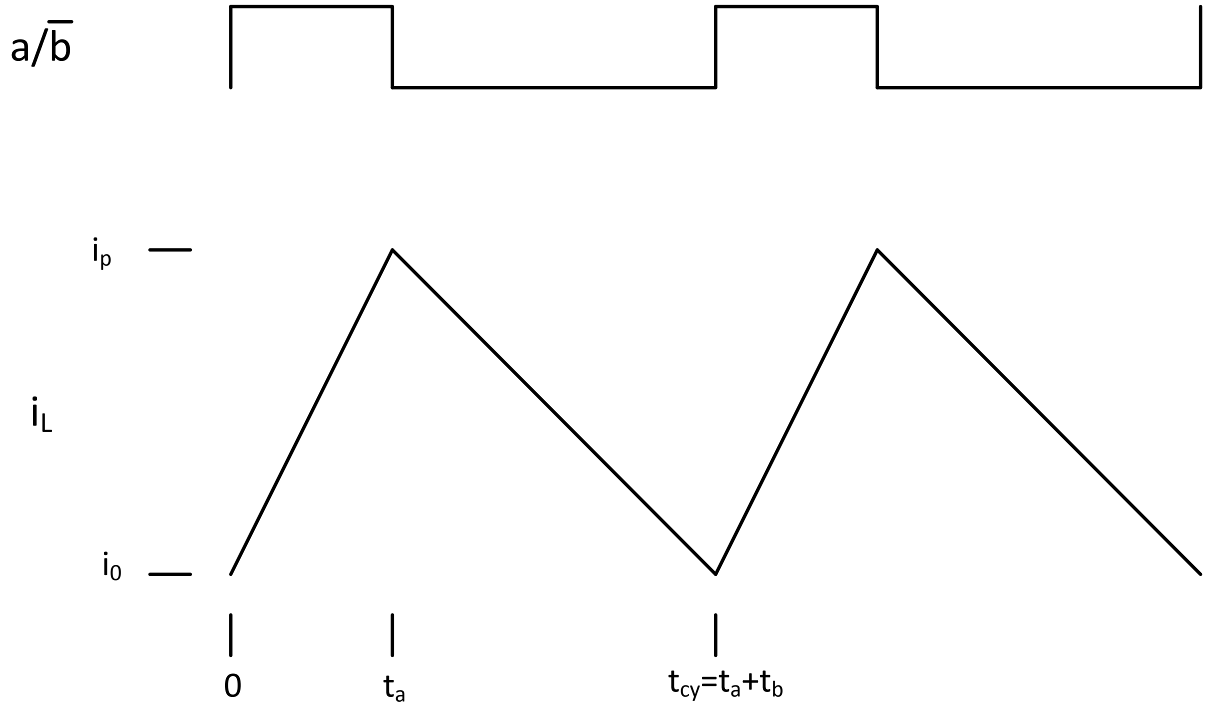
Waveforms



Peak Current

$$i_p = t_a(V_1 - V_2)/L + i_0$$





Periodic Steady State

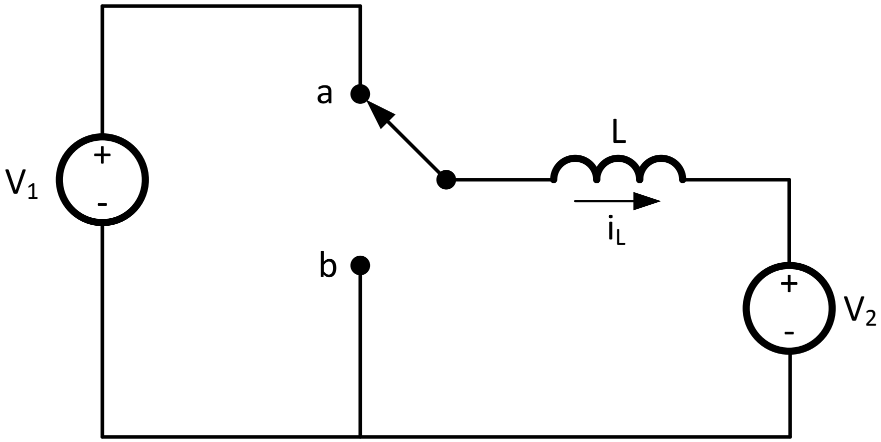
$$\Delta I_a + \Delta I_b = 0$$

$$\frac{t_a\left(V_1 - V_2\right)}{L} + \frac{t_b\left(-V_2\right)}{L} = 0$$

$$t_a\left(V_1 - V_2\right) + t_b\left(-V_2\right) = 0$$

$$t_a V_1 = \left(t_a + t_b\right) V_2$$

$$V_2 = \left(\frac{t_a}{t_a + t_b}\right) V_1 = D V_1$$

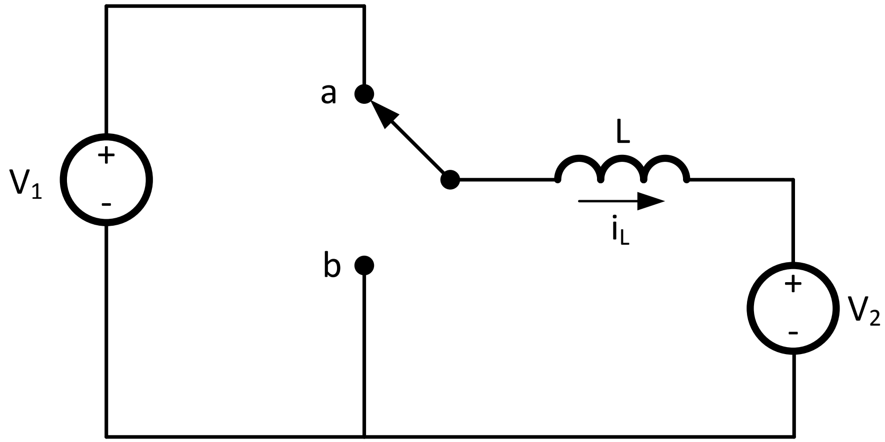


Periodic Steady State

- $V_2 = DV_1$
- Only depends on duty factor D
  - Not on cycle time t_{cy}
  - Not on inductor value L
  - They determine the “ripple”

Simpler Approach

- Look at net volt-seconds on each side of the inductor
- Must be equal in periodic steady state
- DV_1 on left side
- V_2 on right side



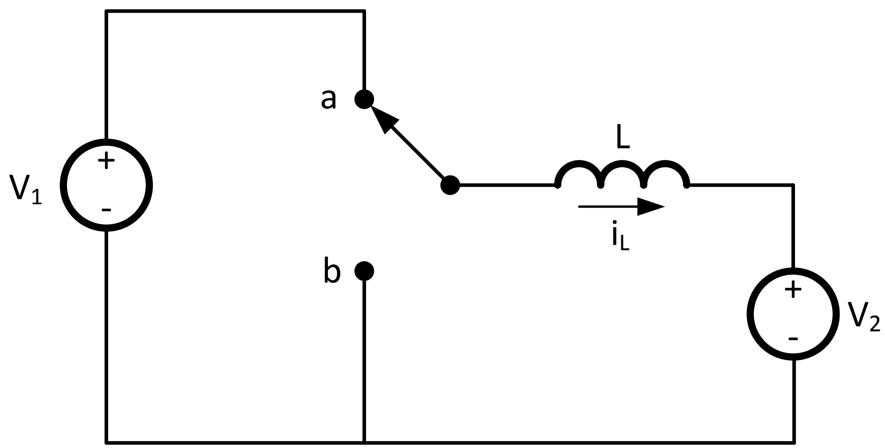
- $DV_1 = V_2$

What if $V_2 \neq DV_1$?

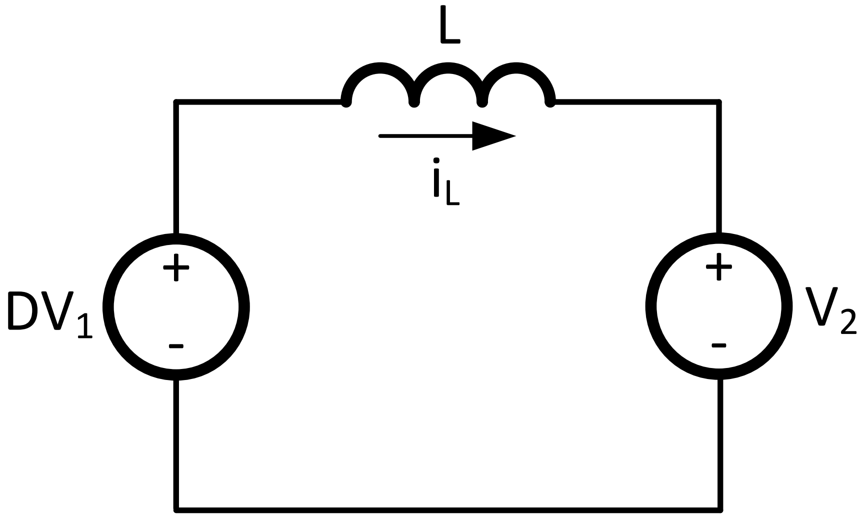
$$\Delta I = \Delta I_a + \Delta I_b$$

$$\Delta I = \frac{t_a\left(V_1 - V_2\right)}{L} + \frac{t_b\left(-V_2\right)}{L}$$

$$\Delta I = \frac{t_{cy}}{L}\left(DV_1 - V_2\right)$$

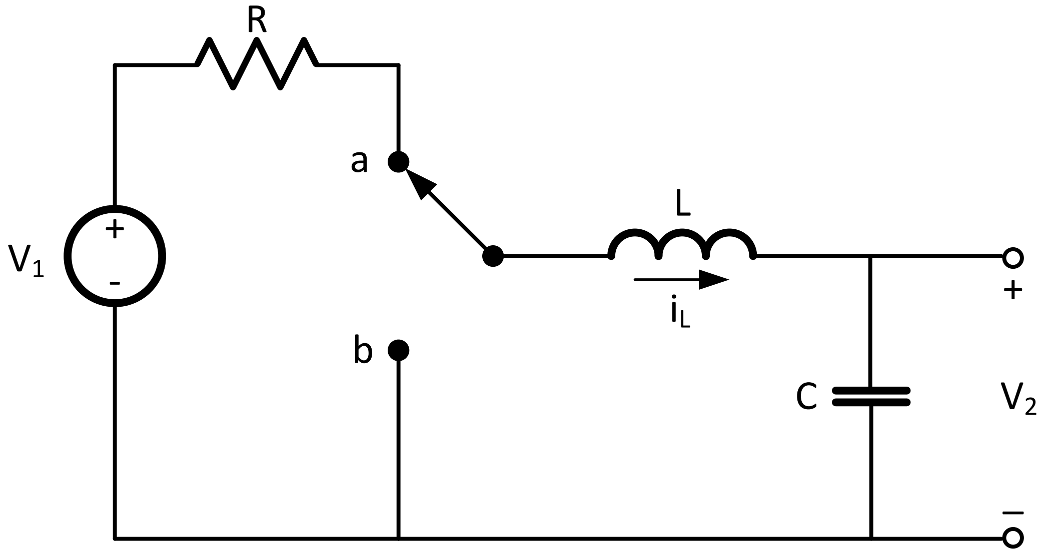


Equivalent Circuit

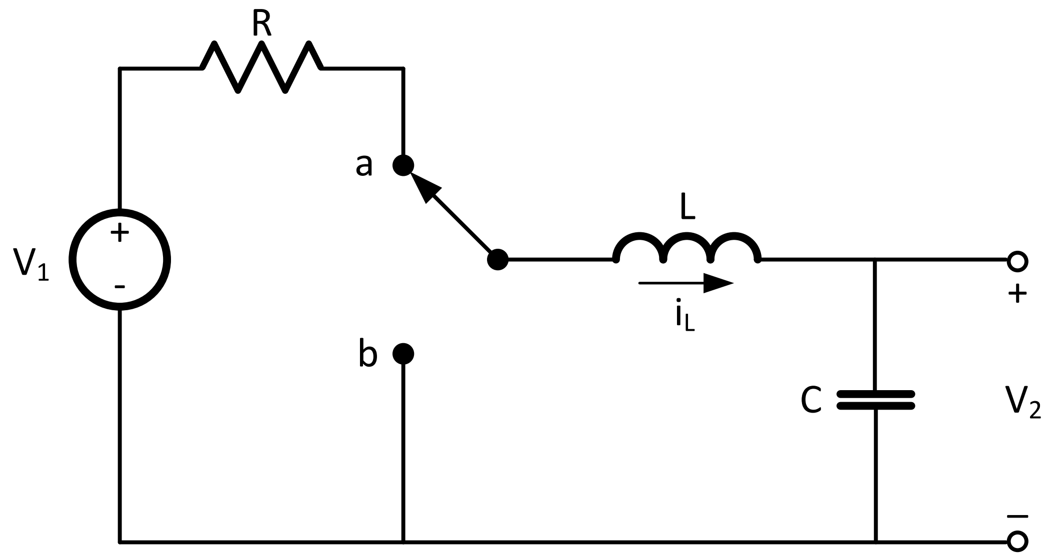


Transient Response

$V_2(0) = 0$, $I_L(0) = 0$.
L = 10uH, C=0.1uF, R=8Ω, D=0.5
What is $V_2(t)$? If $V_1(t>0)$ is 4V.
Switching frequency is high enough you can ignore it.



Transient Response



$$\Delta I = \Delta I_a + \Delta I_b$$

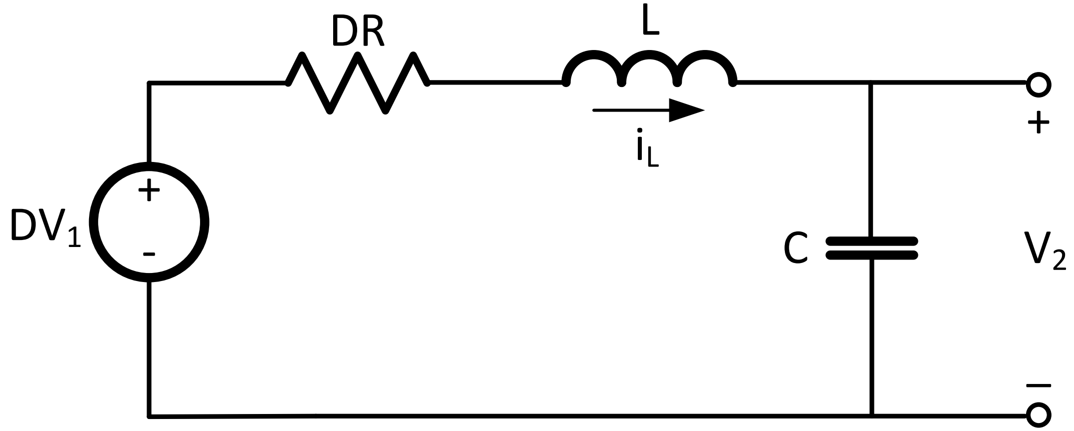
$$\Delta I = \frac{t_a\left(V_1 - IR - V_2\right)}{L} + \frac{t_b\left(-V_2\right)}{L}$$

$$\Delta I = \frac{t_{cy}}{L}\left(DV_1 - DIR - V_2\right)$$

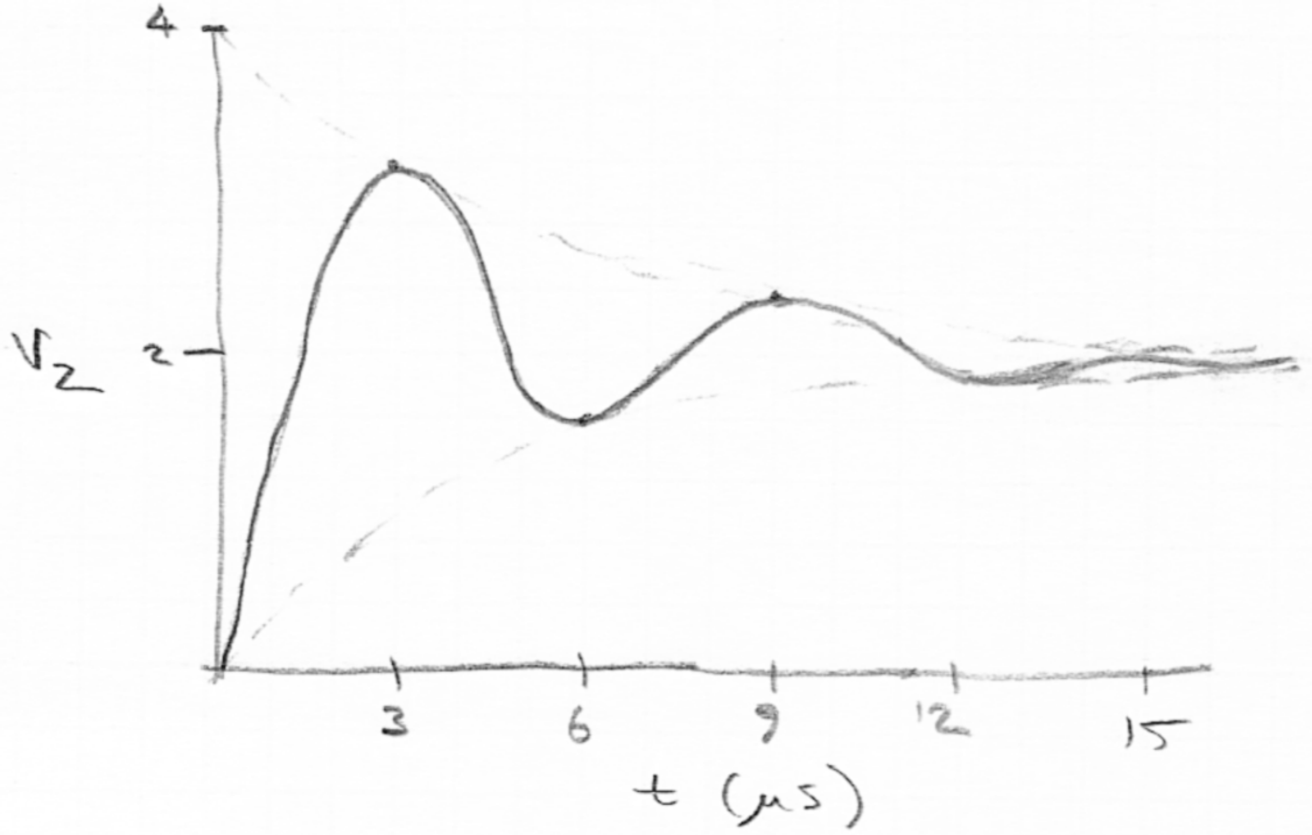
Equivalent Circuit

$$\omega = \frac{1}{\sqrt{LC}} = 1MHz \qquad f = \frac{\omega}{2\pi} = 159kHz$$

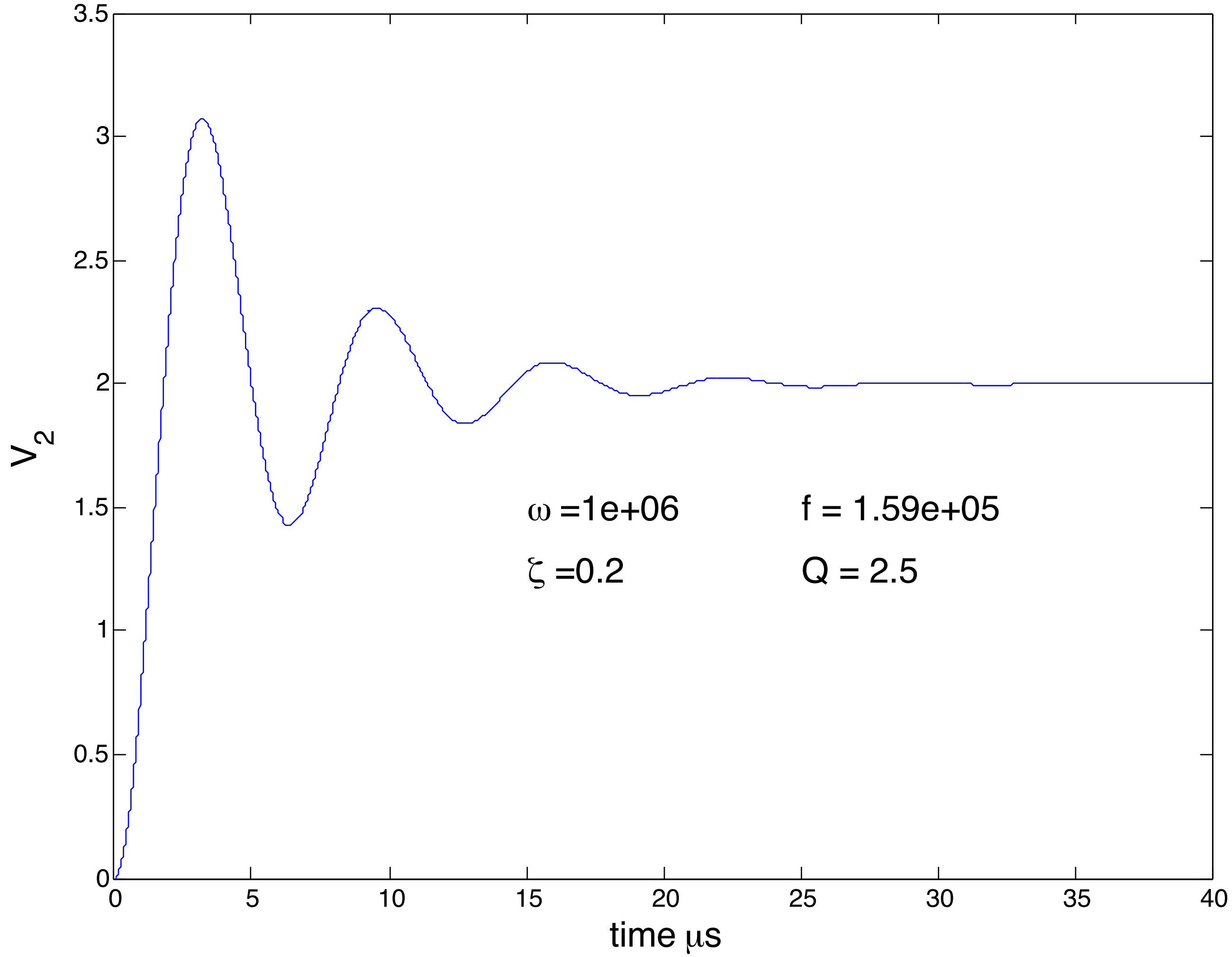
$$\zeta = \frac{DR}{2}\sqrt{\frac{C}{L}} = 0.2 \qquad Q = \frac{1}{2\zeta} = 2.5$$



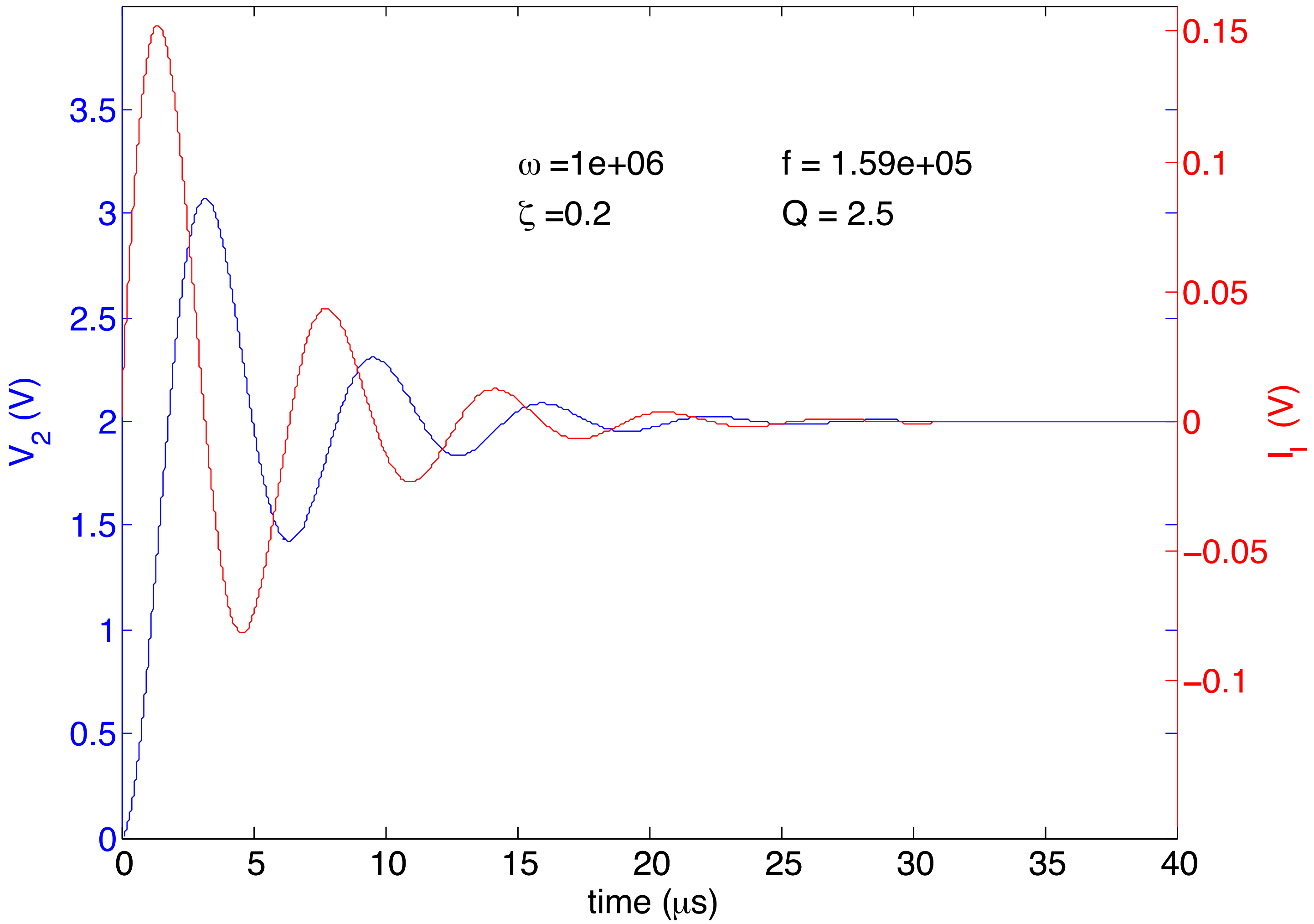
Sketch Response from f and Q



Verify With Simulation

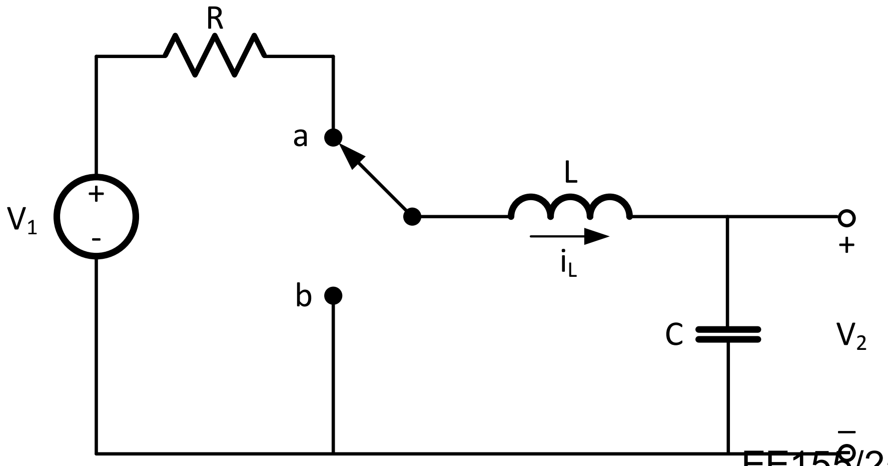


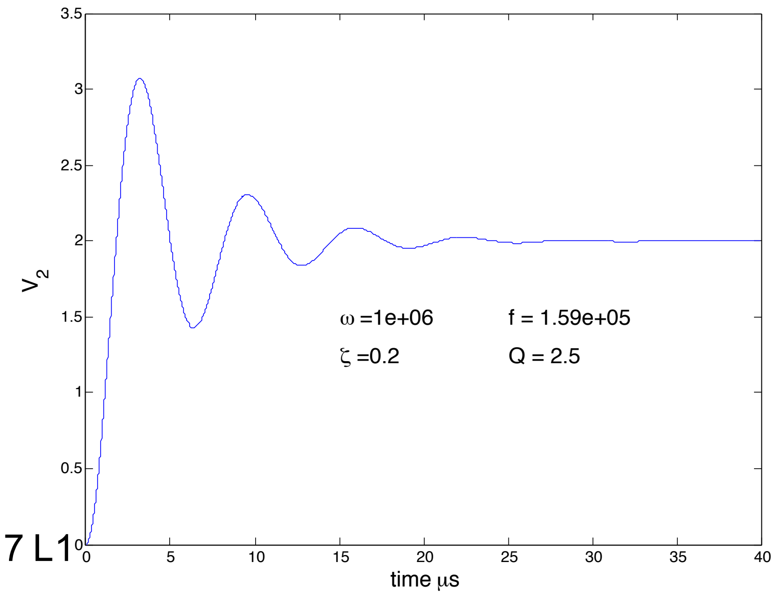
With Current



50% Overshoot

Is this OK?
What if your 5V power supply went to 7.5V on turn-on?

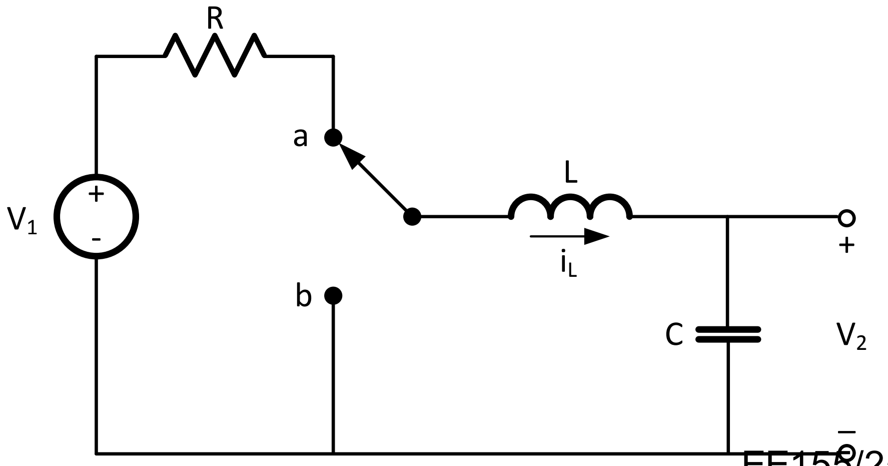


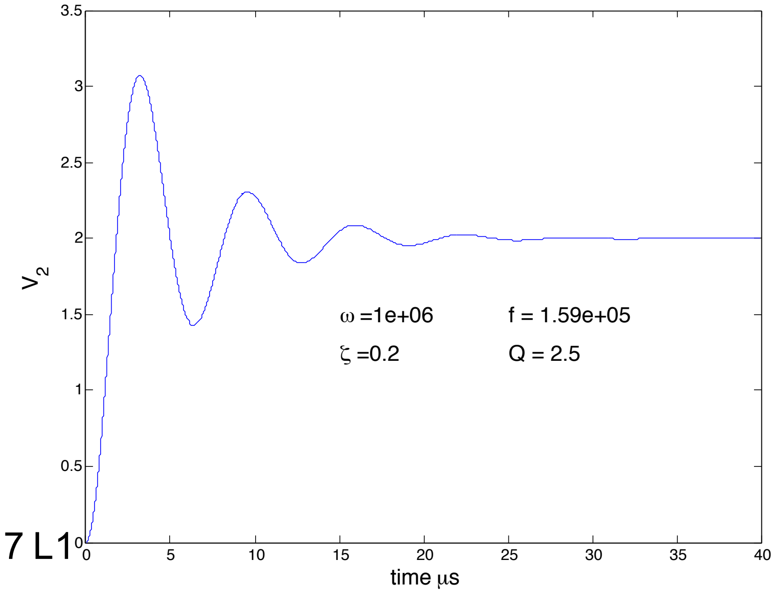


50% Overshoot

Is this OK?
What if your 5V power supply went to 7.5V on turn-on?

It would fry all of your logic chips
Control of switch-mode circuits prevents overshoot



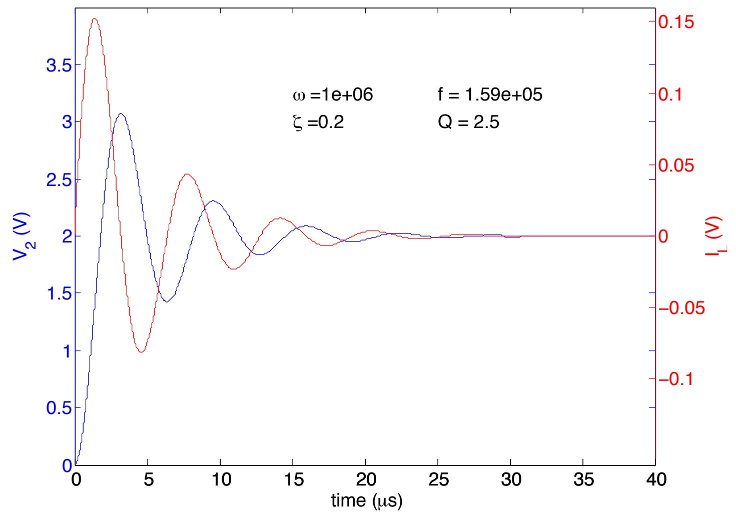


Matlab Model

```
L=1e-5 ;
C=1e-7 ;
R=4 ; % DR
VI=2 ;

dt=1e-8 ;
tsim=4e-5 ;
steps = ceil(tsim/dt) ;

t=0 ;
vc=0 ;
il=0 ;
```




```
% preallocate result arrays to speed simulation
tx=zeros(1,steps) ; vx=zeros(1,steps) ; ix = zeros(1, steps) ;

for i=1:steps
  vl = VI-vc-il*R ;
  vc = vc+il*dt/C ;
  il = il+vl*dt/L ;
  tx(i) = t ; vx(i) = vc ; ix(i) = il ; % log variables
  t=t+dt ;
end
```

Matlab Model

```
L=1e-5 ;
C=1e-7 ;
R=4 ; % DR
VI=2 ;

dt=1e-8 ;
tsim=4e-5 ;
steps = ceil(tsim/dt) ;

t=0 ;
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il=0 ;

% preallocate result arrays to speed simulation
tx=zeros(1,steps) ; vx=zeros(1,steps) ; ix = zeros(1,
steps) ;

for i=1:steps
  vl = VI-vc-il*R ;
  vc = vc+il*dt/C ;
  il = il+vl*dt/L ;
  tx(i) = t ; vx(i) = vc ; ix(i) = il ;
  t=t+dt ;
end
```
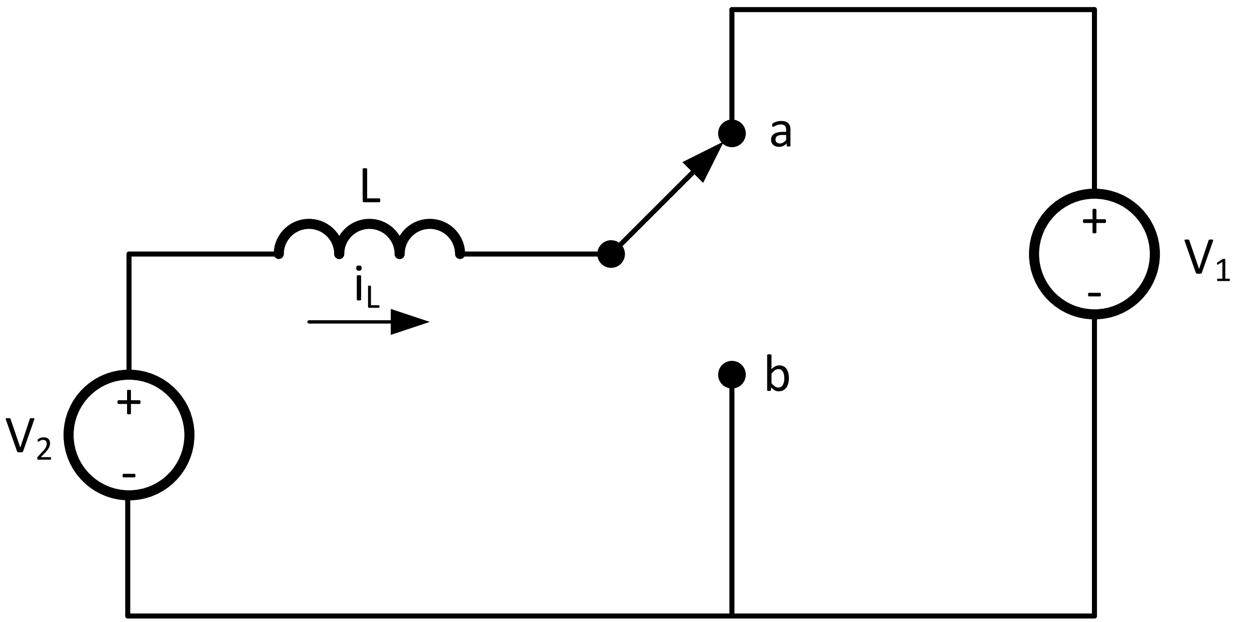
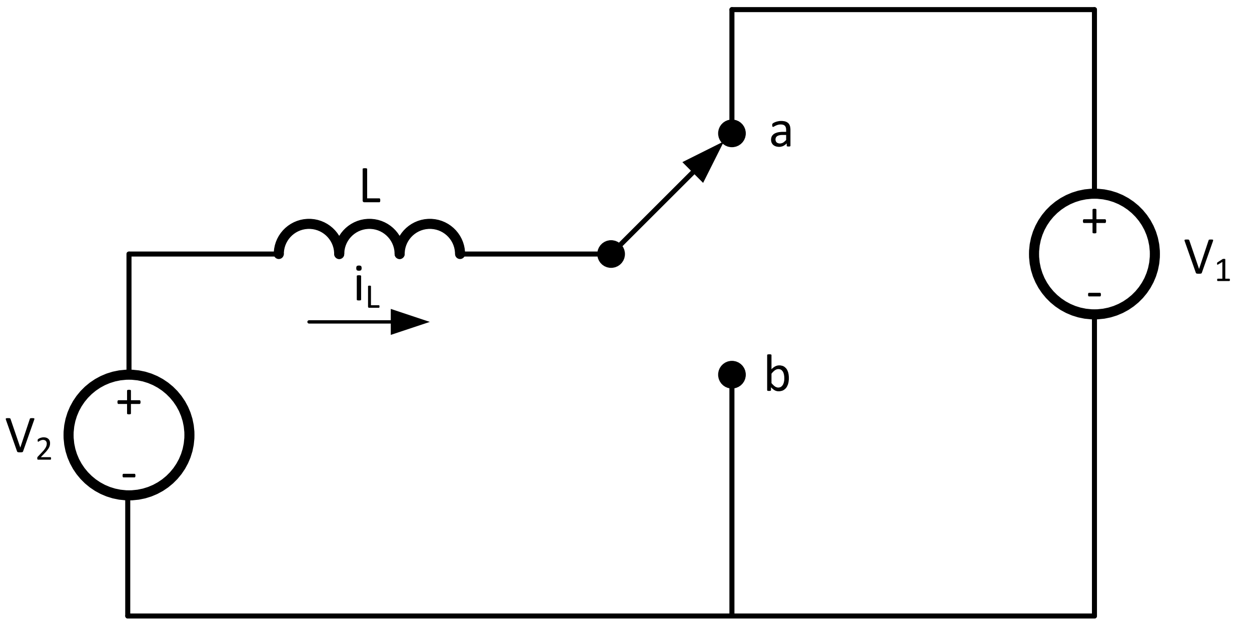

Caution!
Simulation is not a substitute for understanding

Can the Buck Run Backwards?

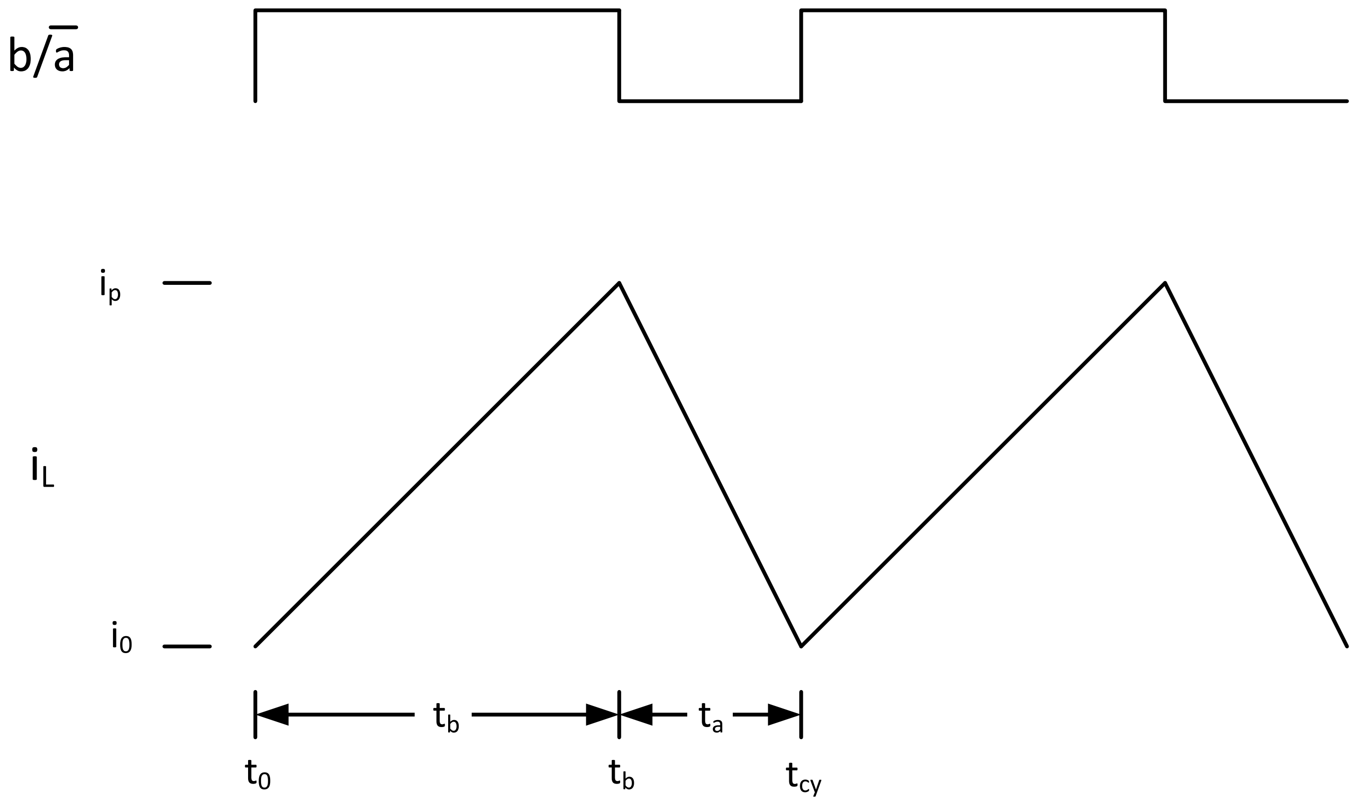


Boost Converter

$$V_1 = \frac{V_2}{D_a} = \frac{V_2}{\left(1 - D_b\right)}$$

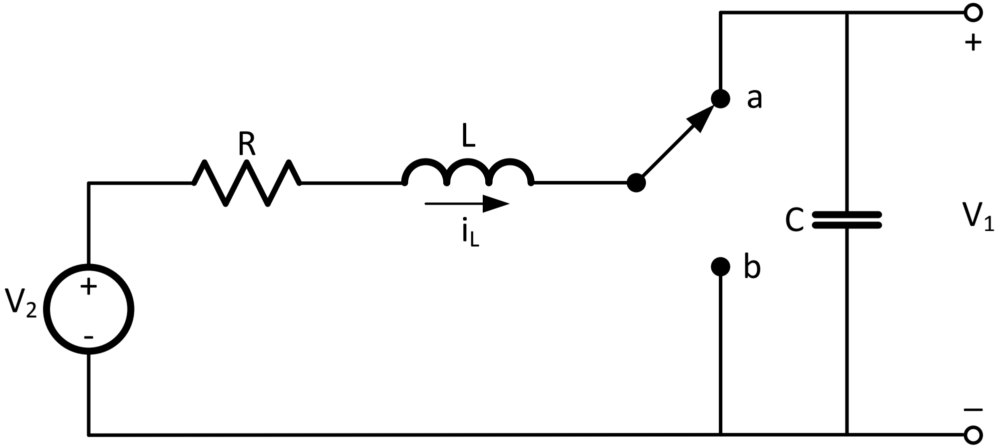


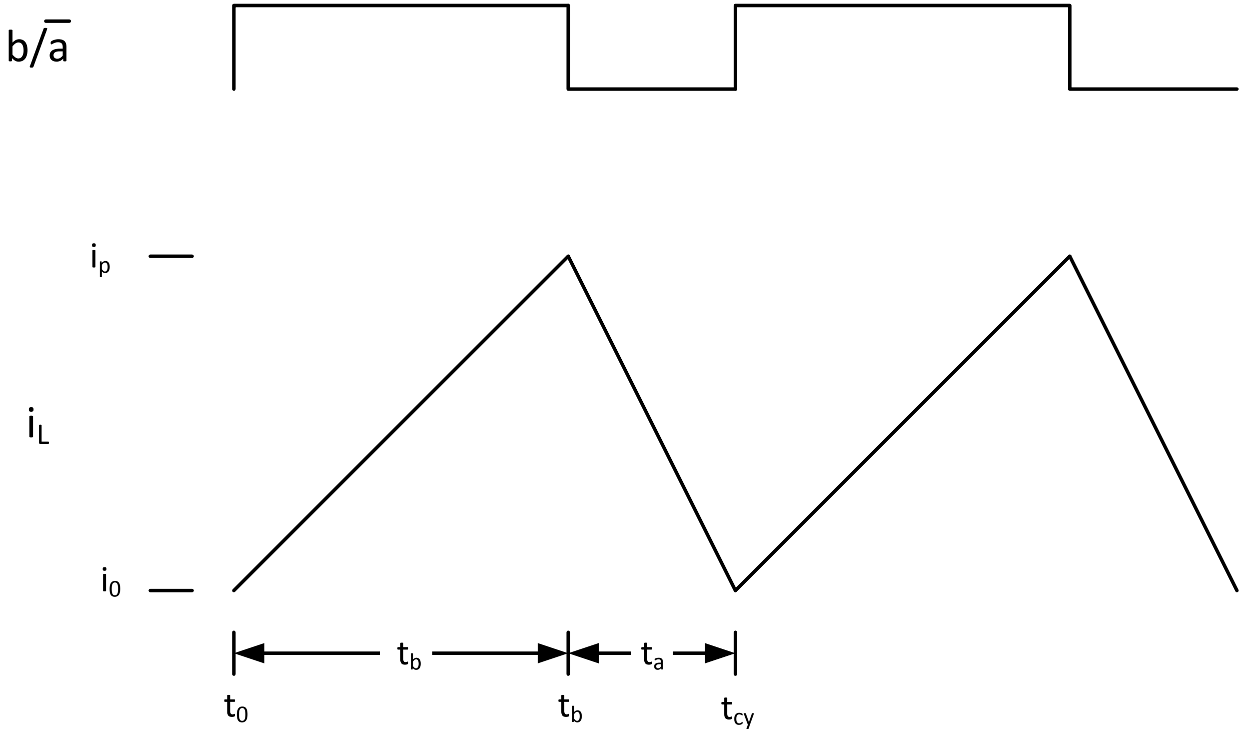
Boost Waveforms



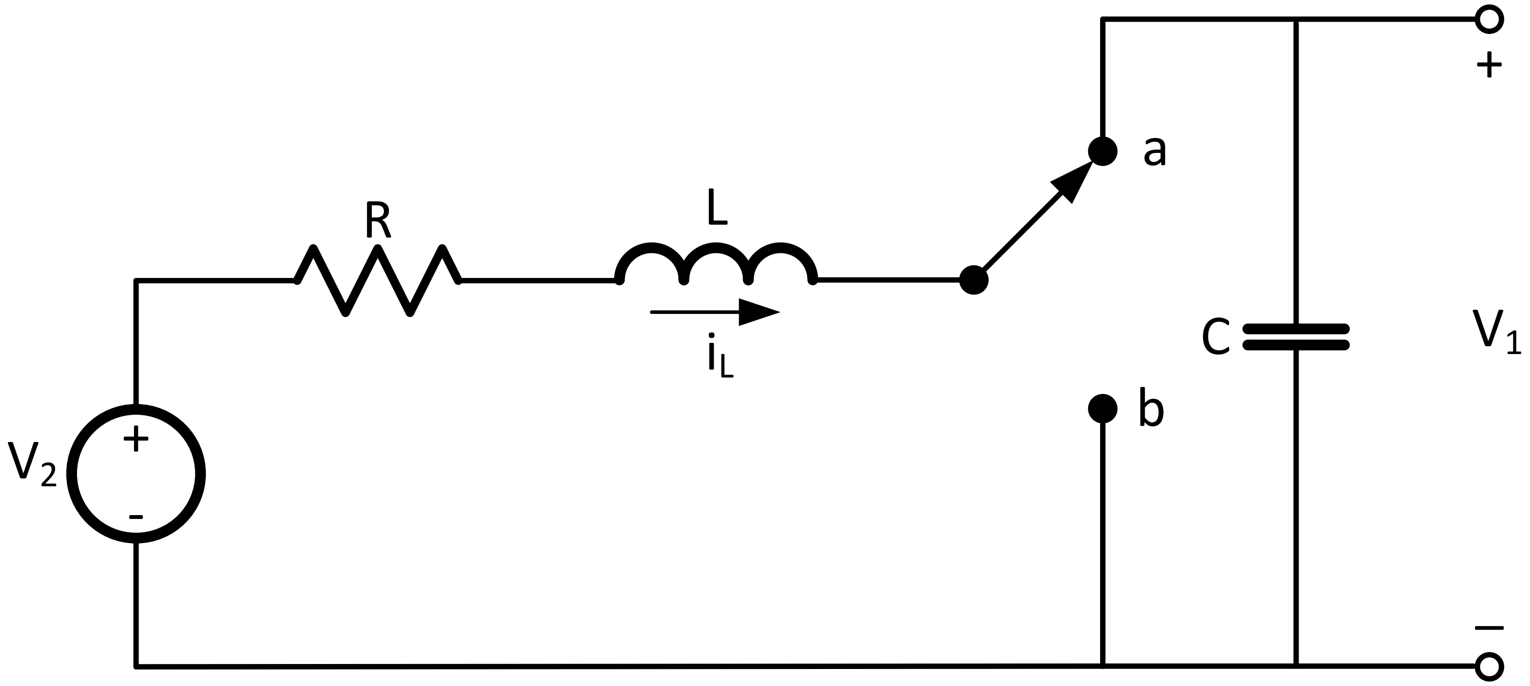
Peak Current

$$i_p = V_2 t_b / L + i_0$$



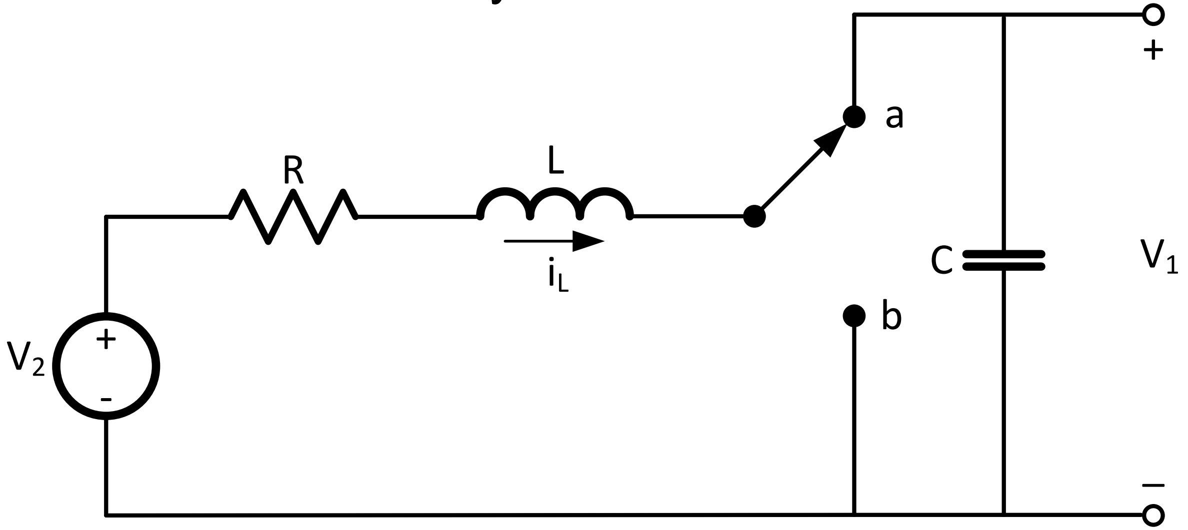


Boost Transient Response
(for $f \ll f_{cy}$)



Boost Transient Response

(for $f \ll f_{cy}$)



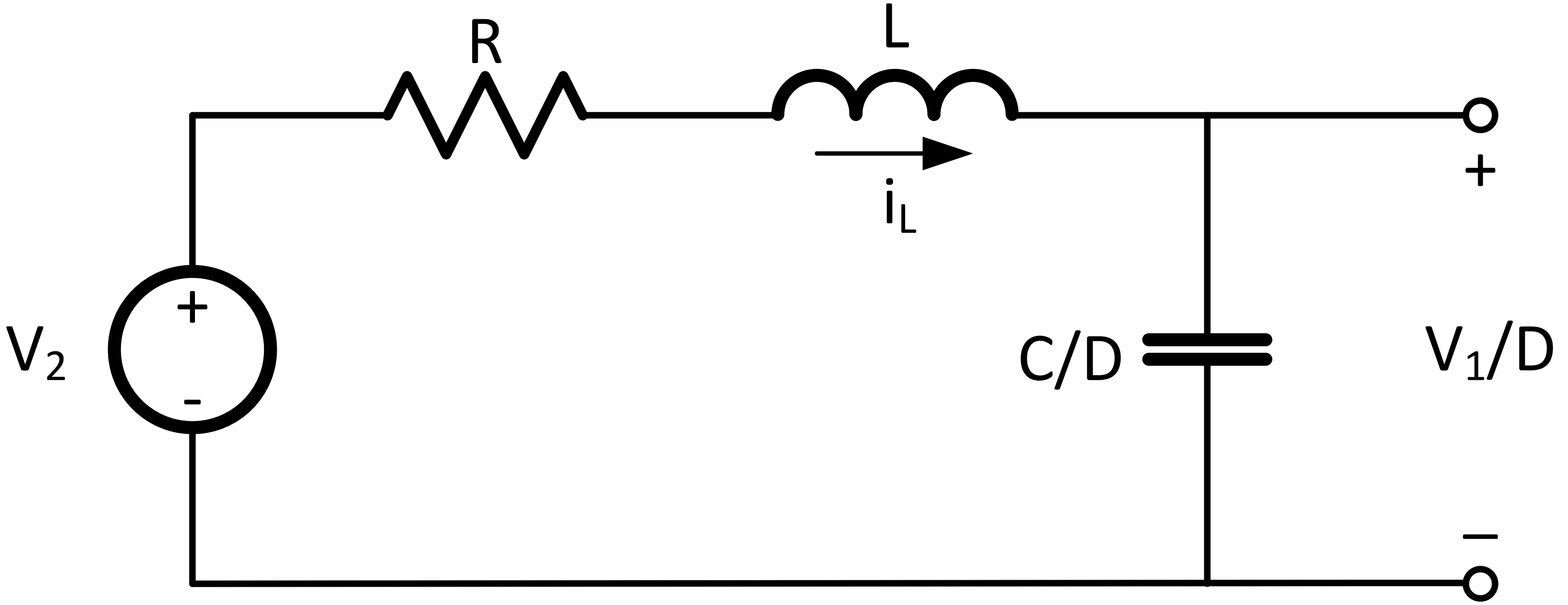
$$\Delta I = \Delta I_a + \Delta I_b$$

$$\Delta I = \frac{t_a\left(V_2 - IR - V_1\right)}{L} + \frac{t_b\left(V_2 - IR\right)}{L}$$

$$\Delta I = \frac{t_{cy}}{L}\left(V_2 - IR - D_a V_1\right)$$

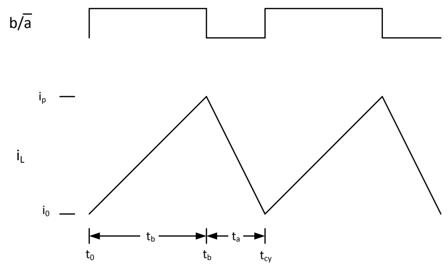
$$\Delta V = \frac{t_a I}{C} = \frac{t_{cy} D I}{C}$$

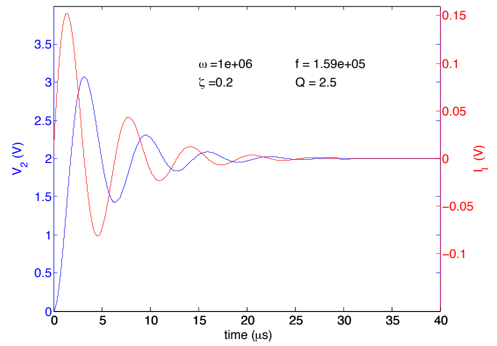
Equivalent Circuit

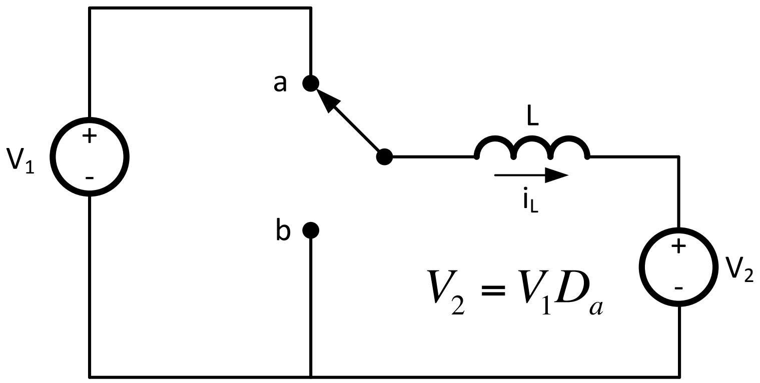


Summary: PWM, PSSA, Buck Boost

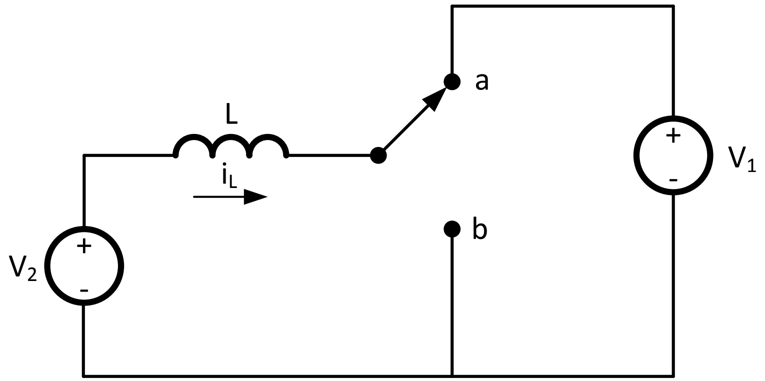
- Separate behavior into fast and slow
  - Fast – within switching cycle
  - Slow – $f \ll f_{cy}$
- Within cycle solve for ***periodic steady state***
  - State variables the same at start and end of cycle.
- For slow transient response
  - Write difference equation
- Buck/Boost Topologies







$$V_2 = V_1 D_a$$



$$V_1 = \frac{V_2}{D_a} = \frac{V_2}{(1 - D_b)}$$

In Upcoming Lectures

No	Date	Topic	HW out	HW in	Lab out	Lab ck	Lab	HW
1	9/25/17	Intro (basic converters)	1		1		Intro to ST32F3	Periodic Steady State
2	9/27/17	Embedded Prog/Power Elect.						
3	10/2/17	Power Electronics - 1 (switches)	2	1	2	1	AC Energy Meter	Power Devices
4	10/4/17	Power Electronics - 2 (circuits)						
5	10/9/17	Photovoltaics	3	2	3	2	PV MPPT	Motor control Matlab
6	10/11/17	Feedback Control						
7	10/16/17	Electric Motors	4	3	4	3	Motor control - Lab/	Feedback
8	10/18/17	Isolated Converters						
9	10/23/17	Solar Day	5/PP	4	5	4	PS	Isolated Converters
10	10/25/17	Magnetics						
11	10/30/17	Soft Switching	6	5/PP	6	5	Magnetics	Magnetics and Inverters
12	11/1/17	Project Discussions						
13	11/6/17	Inverters, Grid, PF, and Batteries		6	P	6	Project	
14	11/8/17	Thermal & EMI						
15	11/13/17	Quiz Review				C1		
16	11/15/17	Grounding, and Debugging						
Q	11/15/17	Quiz - in the evening						
	11/20/17	Thanksgiving Break				C2		
	11/22/17	Thanksgiving Break						
17	11/27/17	Wrapup						
18	11/29/17	Guest Lecture				C3		
19	12/4/17	Guest Lecture						
20	12/6/17	No Class						
	TBD	Project presentations			P			
	12/15/17	Project webpage due						