Cal Poly Sustainable Power for Electrical Resources (SuPER) Project

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Cal Poly SuPER Project

Outline:

• **Background:** rationale for project
• **SuPER prototype development**
• **SuPER simulation model**
• **Applications of simulation**
• **SAI/SETP goals and the Cal Poly SuPER project**
• **Conclusion**
• *Opportunities for research*
Background - Electrification

• Electrification – National Academy of Engineering’s top engineering achievement for the 20th Century

• Estimated 2 billion people (1/3 of population) do not have access
  – Significant proportion of remainder does not have reliable access to battery or grid
  – 18,000 occupied structures on Navajo Nation lack electrical power (2001 legislation)
Background – Solar Insolation

• Goal to provide electrical resources to people in underdeveloped countries
• Leapfrog technology – no need for 100 years of development
  – Example of cell phone
• Review of global insolation map
  – Poorest people ($1-2 a day income)
  – Within plus or minus 30 degree of latitude
    • Highest values of solar insolation (minimum W hr/sq m/day)
Global Solar Insolation (kwh / sq m) worst average month
http://www.sunwise.com/info_center/insolmap.htm
Background – DC Power

• Solar photovoltaic systems inherently DC
• History of DC (Edison) versus AC (Westinghouse and Tesla) at end of 19th and beginning of 20th century
  – DC versus AC for generation, transmission and distribution to loads
  – Initially, lighting was the customer load
  – Thomas P. Hughes; Networks of Power: Electrification in Western Society, 1880-1930; Baltimore: Johns Hopkins University Press, 1983
  – David Nye; Electrifying America Social Meanings of a New Technology, 1880-1940; MIT Press; 1990
Background – DC power loads

- Future lighting technology: DC LEDs
  - 60W incandescent bulb and 15W compact fluorescent bulb lumens
  - Equivalent to 1W LED technology, and improving

- Efficiency of electrical motors: few horsepower
  - Permanent magnet DC motors

- Electrical appliances
  - Computer: 50W laptop (DC)
  - TVs, radios use DC power
  - RV 12V DC market: kitchen appliances
  - Portable power tools – battery powered (DC)

- Computers: wireless connection
  - Internet, phone (voice over IP), TV, radio,
  - Education: MIT Media Lab $100 laptop project
Background – Moore’s Law

- **Stand-alone solar PV system mature technology**

- **Challenge: system design that adapts to improving technology**

- **Application of Moore’s Law to development of SuPER system for two technologies**
  - PV modules
  - Battery/energy storage
Background: Overall Cal Poly
SuPER System Goals

- Design lifecycle of 20 years
- Total Cost: less than $500 for 1 sq m PV module including battery replacements
- Mean time between failures (MTBF): 25 years
- Mean time to repair (MTTR): 1 hour
- Power depends on PV efficiency and battery storage capacity
  - Consideration of load utilization
Why? Broader Impact of SuPER Project

• Provides household electrical power source
  – Only electrical power source for family
  – Increasing power resource with time
  – With financial business plan: $2-3 per month for all electrical power needs

• Decentralized, sustainable development of electrical power in poorest countries

• SuPER system potential resource for raising standard of living of poorest to par with rest of world
Background: Initial Development

Plan

- Five years for completed design, development, and field testing
  - Includes business plan, documentation and dissemination
- First three years for prototype development
  - Three generations at one year for each
- Last two years for field testing
  - Cal Poly sustainable agriculture project
    - Cal Poly Organic Farm
  - Establishing contacts overseas
SuPER Prototype Development – First Year Progress Report

• Summer 2005: White Paper documented
• Fall 2005: 1 NSF and at least 6 foundation proposals submitted; no awards
• Winter 2006: Cal Poly SuPER project lab established in 20-101; initial simulation model completed – 1 senior project
• Spring 2006: BUS 454 four person senior project team develops business/marketing plans
• Summer 2006: initial Phase 0 prototype system implemented - 1 thesis and 3 senior projects
System Testing Block Diagram

Figure 6.1 – Open Loop SuPER System Block Diagram
*Notes:
1) All loads and load probes are represented as one in this diagram.
2) All probes are connected to the USB 5009 via an op amp gain circuit, omitted from this block diagram.
3) The combiner box, which doesn’t appear in the block diagram, junctions all the power lines. For a power flow diagram, focused on the combiner box junction connection, see Figure 5.3.

Stage: Integrate all individual system components to one unit on the cart

System Block Diagram – Phase 1

Figure 4.1 – System Block Diagram
Comparison of Open Loop and Phase 00 Systems

Figure 6.3 – Battery Voltage Level
SuPER Prototype Development – Second Year Progress Report

• Fall 2006: integrated pyranometer for local insolation measurements (G,T)
• Winter 2007: added loads (LED, cooler), initiate motor/ultracapacitor study
• Spring 2007: SuPER system simulation model and Phase 0 prototype system completed – 1 thesis and 6 senior projects
• Summer 2007: dc-dc converter development; proposal being prepared for Solar America Initiative (SAI) / Solar Energy Technologies Program (SETP) University Photovoltaic Process and Product Development Support
Figure 2.1 Photo of SuPER Cart Prototype including Loads
This block diagram varies from the Phase 1 block diagram in only two places:
1) Outback MX-60 instead of DC-DC converter.
2) Open loop PWM signal, since there is no DC-DC converter to interface it with.

Stage: Integrate all individual system components to one unit on the cart.
Figure 2.17 Phase 1 Block Diagram

*Notes:
1) All loads and load probes are represented as one in this diagram.
2) All probes are connected to the USB 6009 via an op amp gain circuit, omitted from this block diagram.
3) The combiner box, which doesn't appear in the block diagram, junctions all the power lines.

Stage: Integrate all individual system components to one unit on the cart.
Figure 2.3 SuPER Power Flow Diagram
Figure 2.5 Status System Interface Block Diagram
Figure 3.1 SuPER Software Flow Diagram
Figure 3.2 SuPER Status and Control Interface Diagram
Primary Control Issues

PV MPPT

Battery SOC

Battery four SOC regions:
SOC <80%, 80-90%, 90-100%, >100%
Charging and discharging (current)

Figure 3.3 BP150SX I-V and Power Curve

Table 2.1 – Deka Battery Charge Voltage Guide [15]

<table>
<thead>
<tr>
<th>Temp. °F</th>
<th>Charge Optimum</th>
<th>Maximum</th>
<th>Float Optimum</th>
<th>Maximum</th>
<th>Temp. °C</th>
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<tr>
<td>≥ 120</td>
<td>13.00</td>
<td>13.30</td>
<td>12.80</td>
<td>13.00</td>
<td>≥ 49</td>
</tr>
<tr>
<td>110 – 120</td>
<td>13.20</td>
<td>13.50</td>
<td>12.90</td>
<td>13.20</td>
<td>44 – 48</td>
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<tr>
<td>100 – 109</td>
<td>13.30</td>
<td>13.60</td>
<td>13.00</td>
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<td>80 – 89</td>
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<td>13.70</td>
<td>14.00</td>
<td>13.40</td>
<td>13.70</td>
<td>21 – 26</td>
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<tr>
<td>50 – 59</td>
<td>14.00</td>
<td>14.30</td>
<td>13.70</td>
<td>14.00</td>
<td>10 – 15</td>
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<tr>
<td>40 – 49</td>
<td>14.20</td>
<td>14.50</td>
<td>13.90</td>
<td>14.20</td>
<td>5 – 9</td>
</tr>
<tr>
<td>≤ 39</td>
<td>14.50</td>
<td>14.80</td>
<td>14.20</td>
<td>14.50</td>
<td>≤ 4</td>
</tr>
</tbody>
</table>
SuPER Simulation Model

• MATLAB/Simulink implementation
  – SimPowerSystems package used
    • DC-DC converter
    • Loads; LEDs, cooler, LEDs, labtop, DC motor, TV
    • Loss model
  – C-MEX S-functions: C rather than .m files
    • PV S-function block
    • Control S-function block
    • Switch control S-function block
    • Battery S-function block
    • Loads: cooler, laptop, dc motor
Figure 4.2 Simulink Model Map
Figure 4.1 SuPER Simulink Model
SuPER Simulation Model

• Separate simulations to develop model
  – DC-DC converter: PSpice and Simulink
  – DC motor with ultracapacitor
  – Cooler
  – Laptop
  – PWM duty cycle
  – LEDs
SuPER Simulation Model

- Prototype system measurements to verify simulation
  - Pyranometer data for local insolation
  - DC motor simulation
  - Battery SOC estimation
  - Cooler operation
  - Laptop battery characteristics
  - LED operation scenarios
SuPER Simulation Model

- DC motor example of simulation/prototype measurement verification
  - Standalone Simulink model of DC motor
  - Issue of transient current/voltage for startup
    - Identification and modeling of behavior
    - Use of ultracapacitor (58F) to protect battery
    - Behavior/timing of steady state: use of resistor model
  - System results: two test cases used
March 19, 2007 SLO Insolation and Temperature
Figures 5.8/5.9 March 19, 2007 Motor Simulation Model Verification
Figure 5.10 March 19, 2007 SOC Estimates
Applications of Simulation
load analysis

- Load demand analysis
  - LED lighting operation
  - Time of motor loading
Loading: 4 LEDs

Figure 5.3 Nighttime LED Operation Simulation
Figure 5.4 Motor Operation Simulation
Application of Simulation
system behavior

• SOC estimation
  - Five load two day scenario one: 1,833 Wh total
    • Motor use each day
  - Five load two day scenario two: 1,583 Wh total
    • Motor use on first day only
  - Four load two day scenario three: 1,399 Wh total
    • Motor use each day without cooler loading
Figure 5.14 Five Load/Two Day Scenario One
Figure 5.15 Five Load/Two Day Scenario Two

SOC Estimation
Figure 5.16 Four Load/Two Day Scenario Three

SOC Estimation

Figure 5.16 Four Load/Two Day Scenario Three
Application of Simulation

- **Results with typical insolation**
- **Peak versus average power**
  - Peak power of motor load (230W demand) met with battery/ultracapacitor
  - Average daily load of at least 700 Wh can be supported by 150 W PV module source with 98 Ah battery/ultracapacitor storage
- **Results validated with prototype system measurements**
Application of Simulation

Preliminary Conclusions

• SOC of battery important system parameter
  - Peak power source during insolation
  - Total power source during non-insolation times

• Load demand is important
  • Schedule of loading of system

• Load factor is important
  • average power / peak power

• Dispatching of power to loads must be included in system design
Cal Poly SuPER Project and SAI

- Primary goals of SuPER project remain
  - Develop technology for households without access to electricity

- SAI goals:
  “The goals of the SAI are to reduce the levelized cost of energy (LCOE) to below 10 ¢/kWh while scaling up manufacturing capacity to supply 5-10 GW of domestic PV installations by 2015” [FOA]
SAI Goals

ref:  http://www1.eere.energy.gov/solar/solar_america/pdfs/inverter_1_intropresentation.pdf
SAI Goals with Estimated impact of Cal Poly SuPER Project

SAI Goal is to make PV cost-competitive by 2015

ref: http://www1.eere.energy.gov/solar/solar_america/pdfs/inverter_1_intropresentation.pdf
SuPER System LCOE Estimates

- Current prototype system estimated system cost ~$1500 with average daily power of 0.700 kWh yields LCOE = 29¢/kWh

- In one year estimated LCOE = 20¢/kWh
  - Expect average daily power of 1 kWh with load dispatching
  - FPGA for laptop, reduce parts count
Conclusions

• Cal Poly SuPER project low tech, small science
• Clear definition of achievable goals
  – Defined metrics to measure progress
• Strong team: faculty, students, industry
• Resources of Cal Poly available to project
• Project fits into Cal Poly’s mission
  – Education
  – Talloires Declaration
Conclusions

- Systems approach to development
  - Digital/computer controlled
  - Simulation model
  - Consideration of loads, load factor, utilization

- DC power distribution to loads
  - Efficiency based upon power electronics
  - New market for DC household appliances
  - LED lighting
Future Efforts: Cal Poly Resources for SuPER Project

- Development laboratory established
  - Power Senior Project Lab (20-101)
  - Also use Power Electronics Lab (20-104)
- Field testing site identified at Cal Poly
  - Cal Poly Organic Farm: part of Sustainable Agriculture Research Center (SARC)
- Faculty team identified: Jim Harris (CPE and EE), Jim Widmann (ME), Dan Waldorf (IE), Neal MacDougall (AGBus/econ), Norm Borin (Marketing), Doug Cerf (Accounting)
- Industrial consultant identified: Jim Medeiros, CEO, Seven Pinnacles Development (SLO)
Cal Poly SuPER Project website URL:

http://www.ee.calpoly.edu/~jharris/research/super_project/super_table_of_contents.htm

Additional Material:
Photos of first year progress
Photos of second year progress
Solar insolation: simulation and measured
Second DC motor simulation data
Photos of SuPER Lab and field test site
Estimate of SuPER prototype cost to date
Future efforts: prototype, simulation, system analysis
Details of cost estimate
Opportunities for Research:

Graduate students are the technical leaders of the undergraduate engineering student team:

- Continued development of simulation of system with MatLab/Simulink, including the study of optimal digital control algorithms and system parameters
- Power system optimization using ETAP
- Porting of control and status software system to FPGA-based technology with integration of sensor and switch capability
- System engineering development of the next generation SuPER system
Opportunities for Research:

Undergraduate students perform specific engineering projects for the SuPER system:
- DC-DC converter development: PV to battery, DC output bus to robust loads
- Modularization and enhancement of the switchboard PCB prototype design
- Battery and ultra-capacitor technology: electrical power storage research and modeling
- Enhanced design of interface to robust set of DC loads: LED, DC motor, battery charging, refrigerator, computer, TV
- *DC network power distribution and protection: NEC code compliance, grounding
- Sensor data acquisition and processing: voltage, current, temperature and sun insolation
- **System engineering: PV input modeling and DC output load scenarios for testing
- Continued development to optimize the white light LED load system
- DC motor characterization and load performance

* Gavin Baskin is working on this for his senior project.

** Alex Liang senior project is analysis and design for field testing at Cal Poly Organic Farm.
Weekly Seminar Meeting in Power Senior Project Room (20-101)
SuPER Project Laboratory
SUPER prototype cart with solar panel, battery, instrumentation and control subsystems
Members present in photo: (left to right) Eran Tal, Eric Phillips, Gustavo Vasquez, Alexander Gee, Jennifer Cao, Sam Muehleck, Dr. Jim Harris, Dr. Taufik, Tyler Sheffield, Dr. Ali Shaban; Members missing: Dr. Ahmad Nafisi, Robert Johnson
Eran Tal working with prototype SuPER System – June 2006
Prototype SuPER System Cart protection and load distribution
12V DC service panel with five load circuits (four in service)

Prototype SuPER System Cart bottom shelf 12V DC 1/4HP motor load and 12V battery

Prototype SuPER System Cart top shelf view
Laptop computer, interface circuits, MX-60 controller

Prototype SuPER System Cart left side
switchboard enclosure main switchboard (bottom) and PV switchboard (top right)
Tyler Sheffield with SuPER prototype – April 2007
Tyler Sheffield and Eran Tal with SuPER prototype in lab (April 2007)
DC motor, dynamometer, battery

Switchboard pcb and motor interface pcb

Ultracapacitor and interface PCB

Circuit breaker panel and five load distribution circuit outlets
LED lights with heat sink

Left side cart view with AC panel for instrumentation

Top of cart with laptop, NI USB-6009 DAQ, and MX-60 (phase 0)

Prototype cart with BP150SX PV module within SuPER laboratory space
Figure 5.1 Golden, Colorado Insolation and Temperature (May)
Figure 5.2 San Luis Obispo Insolation and Temperature (typical March day)
Figure 5.11 March 29, 2007 Insolation and Temperature
Figure 5.12/13  March 29, 2007 Motor Simulation Model Verification
Partial view of SuPER lab area

SuPER prototype and development workstation in lab

View in demonstration area of Cal Poly Organic Farm

Field testing site with pathway with lighting
Field test site with office building with computer and light loads

Field test site packing shed with electrical loads

Field test site greenhouse with electrical loads

Field test site community outreach area
## Estimated SuPER Prototype Costs to Date (Summer 2007)
(supported by return of indirect costs on previous awards to faculty)

<table>
<thead>
<tr>
<th>Infrastructure</th>
<th>Unit</th>
<th>Cost</th>
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<tr>
<td></td>
<td>Dell Inspiron B120 Laptop</td>
<td>$450</td>
</tr>
<tr>
<td></td>
<td>Lind Electronics DC-DC Converter</td>
<td>$140</td>
</tr>
<tr>
<td></td>
<td>BP 150SX Solar Panel</td>
<td>$750</td>
</tr>
<tr>
<td></td>
<td>12V Gel VRLA Battery 98 Ah (20h)</td>
<td>$150</td>
</tr>
<tr>
<td></td>
<td>NI USB-6009 DAQ Devices</td>
<td>$420</td>
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<tr>
<td></td>
<td>Wiring, breakers, connectors, etc.</td>
<td>$460</td>
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<tr>
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<td>PCBs</td>
<td>$400</td>
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<tr>
<td></td>
<td><strong>Subtotal</strong></td>
<td><strong>$2770</strong></td>
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<tr>
<td>Loads</td>
<td>GPX Portable 5” television</td>
<td>$15</td>
</tr>
<tr>
<td></td>
<td>Coleman 12V DC Refrigerator</td>
<td>$90</td>
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<tr>
<td></td>
<td>LED Lights (x4)</td>
<td>$70</td>
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<tr>
<td></td>
<td>Dayton DC motor</td>
<td>$275</td>
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<tr>
<td></td>
<td><strong>Subtotal</strong></td>
<td><strong>$450</strong></td>
</tr>
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</table>

| TOTAL          | **TOTAL**                                                            | **$3220** |
Future Efforts: Simulation Studies

- Use one week as period for system power supply and demand requirements
  - Continue to use worst case monthly insolation data
  - Continue study of system performance under load demand scenarios
- Determine reasonable load demands for family units
  - Review and revise power system requirements
- Complete system power loss/efficiency analysis
  - Critical system components for efficiency and sensitivity
  - Home unit power distribution losses
- Continue to develop battery model
  - Incorporate temperature into simulation model
  - Analyze battery SOC behavior versus lifetime costs
- Continue to verify simulation model with prototype measurements
- Adaptive load demand scheduling / dispatching
Future Efforts: Prototype Development

- DC-DC converter integration
- Laptop to FPGA technology
  - Xilinx Nexys evaluation board
    - Approximately 1 W versus 60 W loading
    - Existing port of uclinux to MicroBlaze soft-core processor
    - Build-in ADC and DAC
- Modularize PCB implementation to reduce mean-time-to-repair (MTTR)
- Analyze system mean-time-to-failure (MTTF)
  - Determine component sensitivities
- Optimize LED lighting circuit implementation
- Design system packaging to satisfy environmental requirements
  - Thermal analysis
- DC power distribution and protection analysis
- Analyze cost to minimize system sustainable lifetime cost
Future Efforts: System Analysis

- Battery technology review for SuPER application
- Alternate power sources to solar PV
  - Source interface to SuPER input system, then to battery and distribution system
  - Substitute sources: thermal, wind, hydro
  - Multiple sources
- Additional loads
  - Cooking and heating
Future Efforts: Cal Poly SuPER Project
Provides Research Opportunities for Student

- **Cal Poly Project Based Learning Institute**
  - New focus for Cal Poly’s engineering education
  - Evolution from senior project requirement
- **Undergraduates and graduates**
  - Graduate students provide leadership/thesis
  - Undergraduates work on senior project
  - Others invited
- **Design/development team environment**
  - Weekly seminar meetings with faculty
- **Funds (faculty provided) available to purchase materials and components for students**
Estimate using Current Prototype Cal Poly SuPER Cost

PV solar module (~1 m²) $750
Battery (@$150 with 2 replace.) 450
subtotal $1200
Remainder of system: 300
  electronics
  power distribution/protection
  packaging
total est. $1500

Note: materials and supplies only
candidly optimistic for remainder