DESIGN AND IMPLEMENTATION OF AN ENERGY-NEUTRAL SOLAR ENERGY SYSTEM FOR WIRELESS SENSOR-ACTUATOR NODES

IEEE Global IoT Summit ’17

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June 2017

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Outline

INTRODUCTION

Introduction

- Wireless sensor/actuator nodes/networks
- Energy-neutral operation
- Energy harvesting, forecasting, and energy-aware design

Objectives

- Extend deployment lifespan
- Reduce labor and maintenance
- Allow for more power-intensive operation

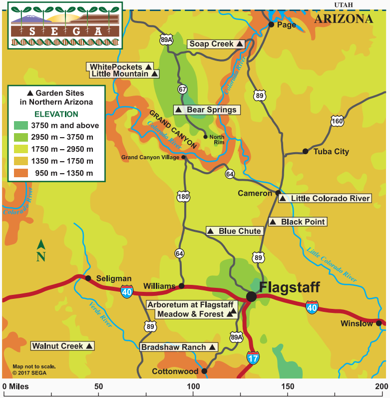
Problem Statement

- Design and implementation of an energy-neutral solar energy system (SES) for wireless sensor/actuator nodes

Southwest Experimental Garden Array (SEGA)

- Explore and quantify ecological/evolutionary responses to climate change
- Geographically-distributed array of highly-instrumented gardens
- Elevation gradient
- Each garden: networks of WiSARD wireless sensor/actuator nodes
- Real-Time Data Center (RTDC)

Garden Sites



Energy Neutral Operation (ENO)

- Energy harvested by the energy source
  - $\eta \int_0^T [P_s(t) - P_c(t)]^+ dt$
  - η - Scaling factor for harvester efficiency
- Energy consumed by the load
  - $\int_0^T [P_c(t) - P_s(t)]^+ dt$
- Energy lost due to leakage
  - $\int_0^T P_{\text{leak}}(t) dt$

$$B_{\min} \leq B_0 + \eta \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{\text{leak}}(t) dt \leq B_{\max}$$

HARDWARE DESIGN AND DEVELOPMENT

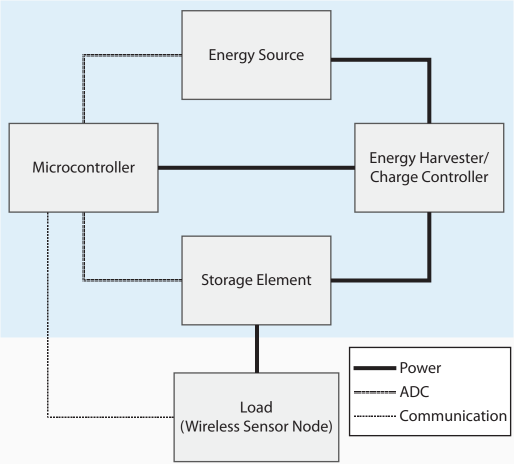


Figure: Block diagram of the SES. Not shown are power management integrated circuits for the microcontroller and the load.

WiSARDNet (Wireless Sensor/Actuator Relay Device Network)

- Modular architecture and hardware implementation
- Self-organizing, self-healing, wireless network

Design Requirements

- 5 V supply
- Source current transients up to 300 mA
- Minimum of three days operation with no energy generation
- Real-time, floating-point analytics
- Voltage and current measurements
- UART Communication

Expected Load Energy Consumption

- WiSARD in typical configuration (2 soil moisture and 3 temperature sensors at 5 minute sampling)
  - $9.25\ \frac{\text{J}}{\text{hour}} \times 24\ \frac{\text{hour}}{\text{day}} = 0.22\ \frac{\text{kJ}}{\text{day}}$
- Worst-case scenario (doubling of transducers, sampling rate, radio communication, losses)
  - $0.22\ \frac{\text{kJ}}{\text{day}} \times 2 \times 2 \times 2 \times 2 = 3.52 \frac{\text{kJ}}{\text{day}}$

Expected solar energy budget

- $E_{\text{harvested}} = I_{\text{avg}} \times A_{\text{panel}} \times C_{\text{panel}} \times C_{\text{harvester}} \times C_{\text{system}} \times 3.6 \times 10^3 \ \frac{\text{kJ}}{\text{day}}$
- $A_{\text{panel}} = 0.002279\text{m}^2,\ C_{\text{panel}} = 0.176,\ C_{\text{harvester}} = 0.8,\ C_{\text{system}} = 0.95$
- Average daily solar insolation by month for Flagstaff, AZ

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Avg Daily Insolation (kWh/m^2 day)	4.57	5.07	6.30	6.65	6.67	6.57	5.68	5.46	6.03	5.85	5.11	4.55

- Expected energy balance for Flagstaff, AZ using daily solar insolation averages by month

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Expected Harvested Energy (kJ/day)	5.02	5.56	6.91	7.30	7.32	7.21	6.23	5.99	6.62	6.42	5.61	4.99
Energy Surplus(+)/Deficit(-) (kJ/day)	+1.50	+2.04	+3.39	+3.78	+3.8	+3.69	+2.71	+2.47	+3.1	+2.90	+2.09	+1.47

Battery Capacity Planning

- Joules to amp-hours (typical configuration)
  - $\text{Total Daily Ah (Ah/day)} = \frac{0.22 \ \frac{\text{kJ}}{\text{day}} \text{day}}{5 \text{ V} \times 3600 \text{ seconds}} = 0.0123 \times 1.5 = 0.0185 \ \frac{\text{Ah}}{\text{day}}$
- Joules to amp-hours (worst-case configuration)
  - $\text{Total Daily Ah (Ah/day)} = \frac{3.52 \ \frac{\text{kJ}}{\text{day}} \ \text{day}}{5 \text{ V} \times 3600 \text{ seconds}} = 0.196 \ \frac{\text{Ah}}{\text{day}}$
- Minimum amp-hours
  - $\frac{\text{Total Daily Ah (Ah/day)} \times \text{Days of autonomy} \times \text{Temperature Multiplier}}{\text{Depth of Discharge}}$
- Minimum amp-hours (typical configuration)
  - $\frac{0.0185 \times 3 \times 1.40}{0.8} = 0.0961\text{Ah} = 97.1\text{mAh}$
- Minimum amp-hours (worst-case configuration)
  - $\frac{0.196 \times 3 \times 1.40}{0.8} = 1.03\text{Ah} = 1030\text{mAh}$
- Comparable price for 2200 mAH lithium-ion

Energy Budget

Battery capacity to Joules

- $B_{\text{full}} = 3.7\ \text{V} \times 2.2\ \text{Ah} \times 0.8 \times 0.75 \times 3.6 \times 10^3 = 17.6\ \text{kJ}$
    - Lithium-ion nominal voltage = 3.7 V
    - Depth of discharge = 0.8
    - Temperature effect scaling factor = 0.75

Case 1

- Time to reach operational mode with a depleted battery
    - $B_{\text{partial}} = \text{V} \ \times \text{Ah} \ \times 3.6 \times 10^3$
    - $B_{\text{discharged}} = 3.0\ \text{V} \times 400\ \text{mAh} \times 3.6 \times 10^3 = 4.32\ \text{kJ}$
    - $B_{\text{operational}} = 3.2\ \text{V} \times 500\ \text{mAh} \times 3.6 \times 10^3 = 5.76\ \text{kJ}$
    - $B_{\text{operational}} = B_{\text{discharged}} + \int_0^T P_{\text{produced}}(t)\, dt - \cancelto{0}{\int_0^T P_{\text{consumed}}(t)\, dt}$
    - $\frac{5.760\ \text{kJ} - 4.32\ \text{kJ}}{5.02\ \text{kJ}} = 0.29\ \text{days}$

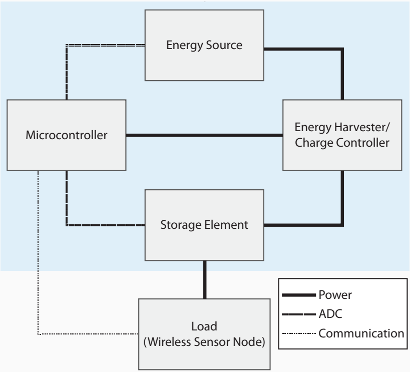
Case 2

- Time to fully discharge the storage element
  - $B_0 = B_{\text{charged}} = 17.6 \text{ kJ}$
  - $0 = B_{\text{charged}} + \cancelto{0}{\int_0^T P_{\text{produced}}(t)\, dt} - \int_0^T P_{\text{consumed}}(t)\, dt$
  - $\frac{17.6 \text{ kJ}}{0.33 \text{ kJ/day}} = 53.3 \text{ days}$

Case 3

- Time to fully discharge the storage element (worst-case configuration)
  - $\frac{17.6 \text{ kJ}}{3.52 \text{ kJ/day}} = 5 \text{ days}$

Block Diagram

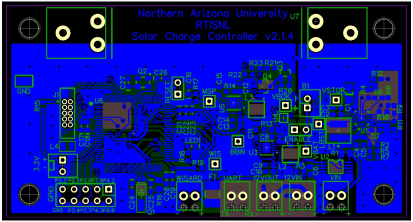


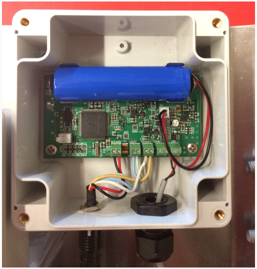
Component Selection

- **Energy Harvester/Charge Controller** - TI BQ25504
- **Energy Source** - SolarMade 1.5 V 150 mA solar panel
- **Microcontroller** - TI MSP432
- **Storage Element** - PKCell ICR18650 2200 mAh lithium-ion
- **Load** - WiSARD

Hardware Design and Development- PCB Design

PCB Layout

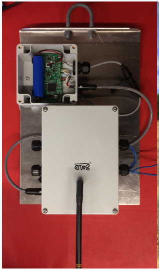




Sections

- Energy harvester
- External IO
- Power conversion
- On-board intelligence

Packaging



SOLAR ENERGY MODEL

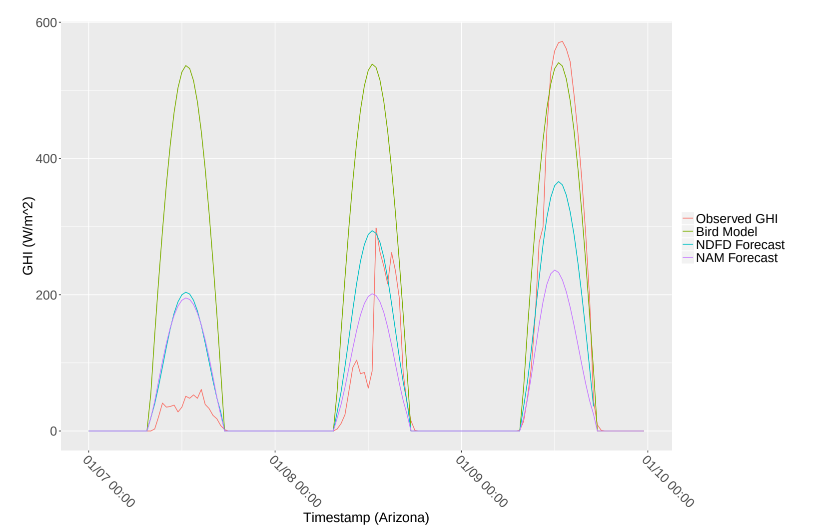
Objective

- Predict GHI
- Convert to energy
- Estimate battery voltage

Models

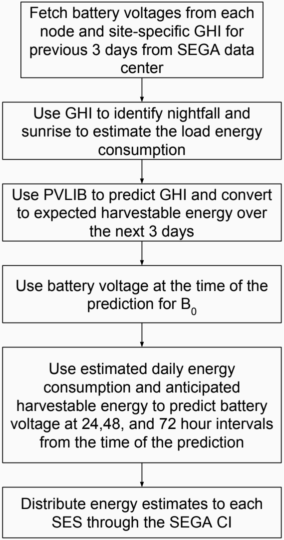
- Bird
- PVLIB
  - North-American Mesoscale (NAM)
  - National Digital Forecast Database (NDFD)

PVLIB vs. Bird January 7-9, 2016



SOFTWARE AND FIRMWARE DESIGN

SES Model



RTDC Software Chain

- Top-level bash script runs as scheduled task
- Fetch observed GHI and battery voltages for each SES
- Run PVLIB to predict GHI over 72 hour interval
- Process observations and predictions, estimate battery voltage at 24, 48, and 72 hours

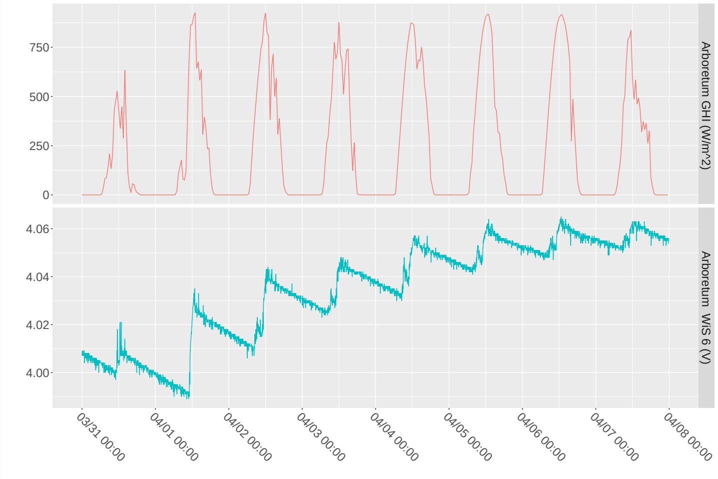
RESULTS

- WiSARD configurations

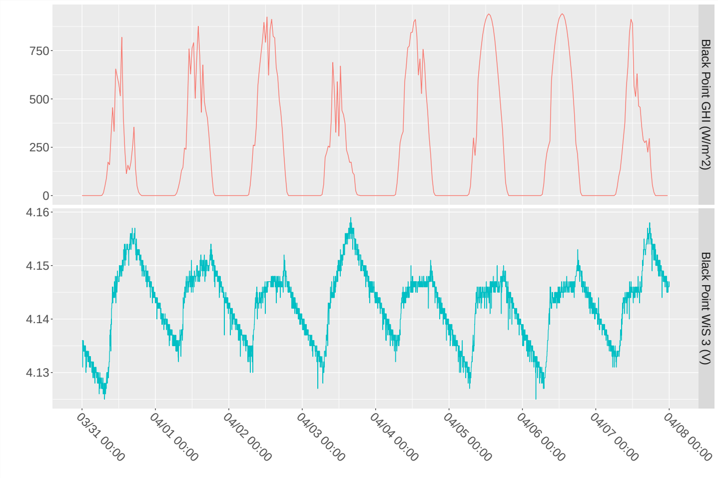
WiSARDNet ID	Garden Site	Sampling Interval	Configuration	Description
6	Flagstaff Arboretum	5 min.	Lizard Model	16 temperature sensors
3	Black Point	5 min.	Soil Moisture	8 soil moisture sensors
10	Bradshaw Ranch	5 min.	MicroMet	3 temperature, 2 soil moisture sensors

- ENO achieved if battery maintains state of charge (above 4.0 V)

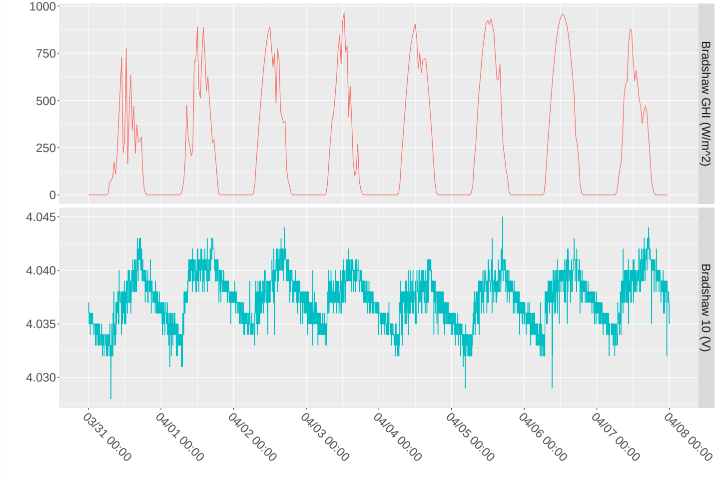
Lizard WiSARD (16 temperature sensors)



Soil Moisture WiSARD (8 soil moisture sensors)



μMet (3 temperature, 2 soil moisture sensors)



Future Work

- Optimize SES firmware
  - Communication protocols (RS-232, I^2C, SPI)
  - Use communication pin as interrupt, enter deeper sleep
  - More robust global variable handling
  - Enable smart task scheduling
- SES model software chain optimization
  - Single language
- SES model implementation
  - Discharge model using different discharge rates and temperatures
  - Machine learning
- SES hardware modification
  - Pin selectable configurations for communication and load output voltage
  - Reduce ground plane noise

Thank you!

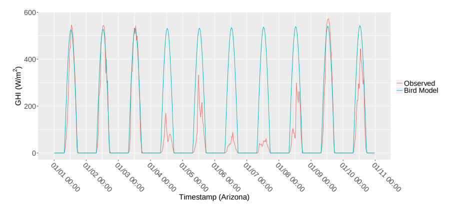
Off-the-shelf Solutions

- Seeed Studio/XBee Carrier
- Adafruit charge controller PCB
- SparkFun's Sunny Buddy PCB

Issues

- Field-ready
- Communication interfaces
- Not low-power

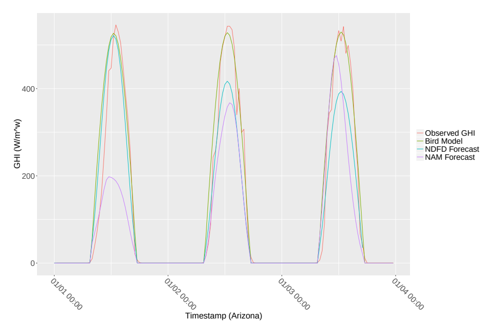
Bird Model



- The Bird model GHI prediction compared with observed GHI at The Arboretum at Flagstaff over a 10-day period in January, 2016

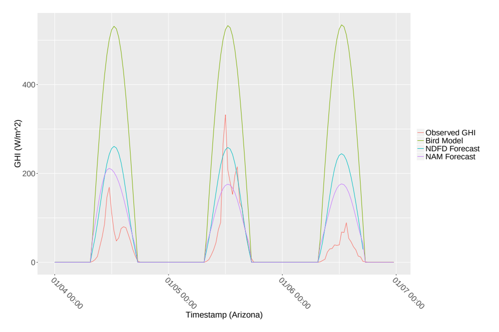
Period	RMSE $\left(\frac{\mathbf{W}}{\mathbf{m^2}}\right)$	MAE $\left(\frac{\mathbf{W}}{\mathbf{m^2}}\right)$	MBE $\left(\frac{\mathbf{W}}{\mathbf{m^2}}\right)$
Bird (Jan 1-3)	45.84	21.25	13.6
Bird (Jan 4-6)	193.2	111.5	111.3
Bird (Jan 7-9)	161.5	80.8	74.4
Bird (Jan 1-10)	143.2	69.29	65.0

PVLIB vs. Bird January 1-3, 2016



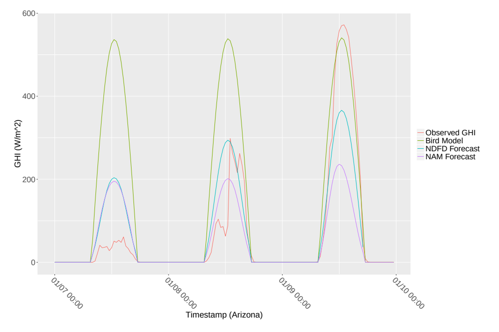
Model	RMSE $\left(\frac{\mathbf{W}}{\mathbf{m^2}}\right)$	MAE $\left(\frac{\mathbf{W}}{\mathbf{m^2}}\right)$	MBE $\left(\frac{\mathbf{W}}{\mathbf{m^2}}\right)$
Bird	48.07	23.29	15.05
NDFD	63.22	36.44	-18.62
NAM	109.29	56.7	-49.27

PVLIB vs. Bird January 4-6, 2016



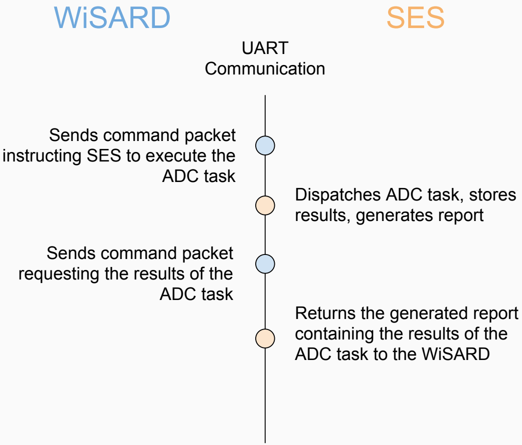
Model	RMSE $\left(\frac{\mathbf{W}}{\mathbf{m}^2}\right)$	MAE $\left(\frac{\mathbf{W}}{\mathbf{m}^2}\right)$	MBE $\left(\frac{\mathbf{W}}{\mathbf{m}^2}\right)$
Bird	201.8	121.7	121.5
NDFD	70.13	38.69	36.49
NAM	53.24	30.84	23.83

PVLIB vs. Bird January 7-9, 2016



Model	RMSE $\left(\frac{\mathbf{W}}{\mathbf{m^2}}\right)$	MAE $\left(\frac{\mathbf{W}}{\mathbf{m^2}}\right)$	MBE $\left(\frac{\mathbf{W}}{\mathbf{m^2}}\right)$
Bird	168.77	88.13	81.29
NDFD	79.66	42.77	3.88
NAM	105.42	53.49	-17.27

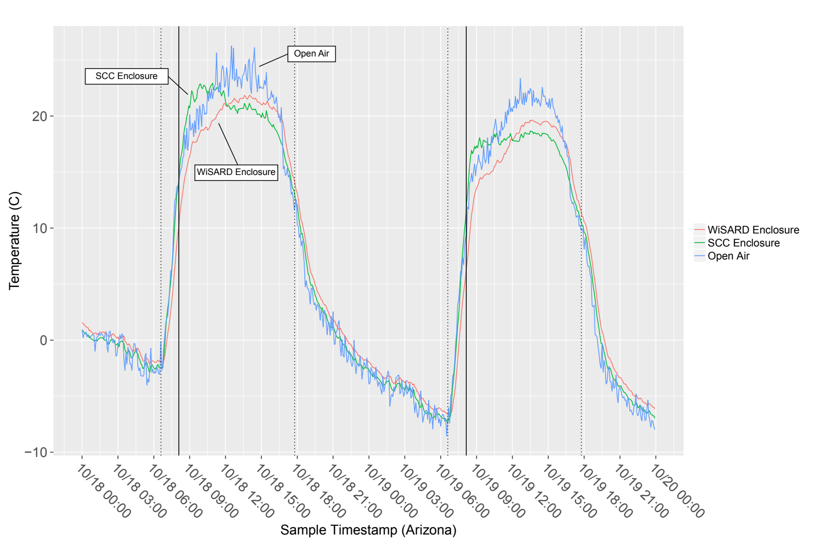
WiSARD-SES Communication Protocol



Quantifying model performance

- Typical operating range: 4.15 - 3.4 V (750 mV)
- Acceptable error: $\pm 37.5\ \mathrm{mV}$

Date	Predicted Voltage (V)	Observed Voltage (V)	Error (mV)
02/17/2017	—	3.790	—
02/18/2017	3.757	3.737	20
02/19/2017	3.735	3.725	10
02/20/2017	3.744	3.729	15
02/21/2017	—	3.760	—
02/22/2017	3.763	3.775	-12
02/23/2017	3.790	3.796	-6
02/24/2017	3.829	3.855	-26


Open Air
SCC Enclosure
WiSARD Enclosure
Temperature (C)
20
10
0
−10
10/18 00:00
10/18 03:00
10/18 06:00
10/18 09:00
10/18 12:00
10/18 15:00
10/18 18:00
10/18 21:00
10/19 00:00
10/19 03:00
10/19 06:00
10/19 09:00
10/19 12:00
10/19 15:00
10/19 18:00
10/19 21:00
10/20 00:00
Sample Timestamp (Arizona)
WiSARD Enclosure
SCC Enclosure
Open Air

Real-Time Data Center (RTDC)

- Collects observed GHI and battery voltage for each SES
- Runs GHI prediction model
- Distributes battery voltage predictions to each SES

SES Firmware

- MSP432
- Task execution
- UART communication with WiSARD

Results- Model Performance

SES Firmware

- Written with Code Composer Studio (TI) in embedded C
- UART communication
  - Command, data request, interrogate, HID
- ADC readings for battery voltage and solar panel voltage, current
- Error reporting
- Parsing model results (unimplemented)