Solar Design Algorithm

The document below defines the calculations used to design and evaluate a PV system in preparation for creating electrical drawings.
Most of the computer code is detailed below, and the full system calculation code is found here (https://github.com/kshowalter/SPD_server/blob/master/lib/calculate_system.js). This algorithm is currently implemented in Javascript. The "Javascript" labeled boxes below is the actual code used in FSEC's application code.

Note: For each section the symbols are pre-pended by a section name when stored as a variable in the computer code, in the form of "section.symbol".

System specification

These are the what uniquely define the system design. Every other value is deterministically caclated from these variables. These are the user input in FSEC's online express design application.

Description	Symbol	Unit
Inverter manufacturer name	inverter.manufacturer_name	-
Inverter model	inverter.device_model_number	-
Module manufacturer name	array.manufacturer_name	-
Module model	array.device_model_number	-
Grid voltage	inverter.grid_voltage	V
Number of PV Source Circuits	array.num_of_strings	ea.
Total Number of Modules	array.num_of_modules	ea.
Maximum Number of Series-Connected Modules per Source Circuit	array.largest_string	ea.
Minimum Number of Series-Connected Modules per Source Circuit	array.smallest_string	ea.
Minimum Distance Above Roof (in)	module.array_offset_from_roof	in.
Grid type	interconnection.grid_type	-
Grid options	interconnection.grid_options	-
Connection type	interconnection.connection_type	-
Main panel supply OCPD rating (A)	interconnection.supply_ocpd_rating	A
Main panel busbar rating (A)	interconnection.bussbar_rating	A
Sum of inverter output overcurrent protection devices (A)	interconnection.inverter_ocpd_dev_sum	A
Sum of inverter(s) output circuit current (A)	interconnection.inverter_output_cur_sum	A
Total of load breakers (A)	interconnection.load_breaker_total	A

Constants

These are fixed values that are not calculated or provided by the user.

Description	Symbol	Limits	Value used	Unit
2% Maximum Temperature	array.max_temp	In Florida: 30 to 36	36	°C
Extreme Annual Mean Minimum Design Dry Bulb Temperature	array.min_temp	In Florida: -9 to 11	-9	°C
Maximum Voltage Rating?	array.code_limit_max_voltage	600	600	V

The most extreme temperatures are used so that the designed system is usable anywhere in Florida.

```
array.max_temp = 36;
array.min_temp = -9;
array.code_limit_max_voltage = 600;
```

Manufacturer data

The following information is taken from the manufacturer specification sheets. In our online express design application, this information is stored in FSEC's database.

Inverter:

Description	Symbol	Unit
UL1741 listed/FSEC approved?	inverter.ul_1741	-
Is inverter tranformerless	inverter.tranformerless	-
Is this a microinverter	?	V
Maximum dc voltage, Vmax,inv (V)	inverter.vmax	V
MPPT minimum dc operating voltage (V)	inverter.mppt_min	V
MPPT maximum operating voltage (V)	inverter.mppt_max	V
Min. dc operating voltage (V)	inverter.voltage_range_min	V
Min. dc start voltage (V)	inverter.vstart	V
Maximum dc operating current per inverter input or MPP tracker (A)	inverter.imax_channel	A
Number of inverter inputs or MPP trackers	inverter.mppt_channels	A
Maximum OCPD Rating (A)	inverter.max_ac_ocpd	A
Imax total	inverter.imax_total	A
Imax per MPPT channel	inverter.imax_channel	A
Max DC input power 120	inverter.max_dc_inputpower_120	W
Max DC input power 208	inverter.max_dc_inputpower_208	W
Max DC input power 240	inverter.max_dc_inputpower_240	W
Max DC input power 277	inverter.max_dc_inputpower_277	W
Max DC input power 480	inverter.max_dc_inputpower_480	W
Nominal AC output power 120	inverter.nominal_ac_output_power_120	W
Nominal AC output power 208	inverter.nominal_ac_output_power_208	W
Nominal AC output power 240	inverter.nominal_ac_output_power_240	W
Nominal AC output power 277	inverter.nominal_ac_output_power_277	W
Nominal AC output power 480	inverter.nominal_ac_output_power_480	W
Max AC output current 120	inverter.max_ac_output_current_120	V
Max AC output current 208	inverter.max_ac_output_current_208	V
Max AC output current 240	inverter.max_ac_output_current_240	V
Max AC output current 277	inverter.max_ac_output_current_277	V
Max AC output current 480	inverter.max_ac_output_current_480	V

Module:

Description	Symbol	Unit
Description	Symbol	Unit
FSEC certified	module.FSEC_approved	-
Maximum power @ STC (W)	module.pmp	W
Open-circuit voltage @ STC (V)	module.voc	V
Short-circuit current @ STC (A)	module.isc	A
Maximum power voltage @ STC (V)	module.vmp	V
Maximum power current @ STC (A)	module.imp	A
Maximum overcurrent device rating (A)	module.max_series_fuse	A
Maximum system voltage rating (V)	module.max_system_v	V
Temp Coeff Voc (%/°C)	module.tc_voc_percent	%/°C
Temp Coeff Vmp (%/°C)	module.tc_vpmax_percent	%/°C
Nameplate rating	module.nameplaterating	W

Calculations

Modules, source circuits, and array

Calculation summary:

Description	Symbol	Calculation
Maximum Power (W)	source.max_power	module.pmp * array.largest_string
Open-Circuit Voltage (V)	source.voc	module.voc * array.largest_string
Short-Circuit Current (A)	source.isc	module.isc
Maximum Power Voltage (V)	source.vmp	module.vmp * array.largest_string
Maximum Power Current (A)	source.imp	module.imp
Source Circuit Maximum Current (A), Isc x 1.25	source.Isc_adjusted	module.isc * 1.25
Voltage Correction Factor	array.voltage_correction_factor	sf.if(array.min_temp < -5, 1.12, 1.14)
Maximum system voltage Option 1 (module temp. correction factor)	array.max_sys_voltage_2	source.voc * (1 + module.tc_voc_percent / 100 * (array.min_temp - 2
Maximum system voltage Option 1 (general temp. correction factor)	array.max_sys_voltage_1	source.voc * array.voltage_correction_factor
Maximum system voltage	array.max_sys_voltage	sf.max(array.max_sys_voltage_1, array.max_sys_voltage_2)
Minimum array voltage (module temp. correction factor)	array.min_voltage	array.smallest_string * module.vmp * (1 + module.tc_vpmax_percent
Maximum Power (W)	array.pmp	array.num_of_modules * module.pmp
Open-Circuit Voltage (V)	array.voc	source.voc
Short-Circuit Current (A)	array.isc	module.isc * array.num_of_strings
Maximum Power Voltage (V)	array.vmp	module.vmp * array.largest_string
Maximum Power Current (A)	array.imp	module.imp * array.num_of_strings
PV Power Source Maximum Current (A)	array.isc_adjusted	array.isc * 1.25
PV Power Source Maximum Voltage (V)	array.vmp_adjusted	array.max_sys_voltage_2
PV Power Source Minimum Voltage (V)	array.vmp_adjusted_min	???
Enter Maximum Number of Parallel Source Circuits per Output Circuit (1-2)	array.circuits_per_MPPT	Math.ceil(array.num_of_strings / inverter.mppt_channels)
PV Output Circuit Maximum Current (A)	array.combined_isc	source.isc * array.circuits_per_MPPT
PV Output Circuit Maximum Current (A), Isc x 1.25	array.combined_isc_adjusted	module.isc * 1.25 * array.circuits_per_MPPT
Maximum PV Output Circuit Voltage at Lowest Temperature	array.max_sys_voltage_2	array.max_sys_voltage_2

```
source.max_power = module.pmp * array.largest_string;
source.voc = module.voc * array.largest_string;
source.isc = module.isc;
source.vmp = module.vmp * array.largest_string;
source.imp = module.imp;
source.Isc_adjusted = module.isc * 1.25;
array.voltage_correction_factor = sf.if( array.min_temp < -5, 1.12, 1.14);
array.max_sys_voltage_1 = source.voc * array.voltage_correction_factor;
array.max_sys_voltage_2 = source.voc * ( 1 + module.tc_voc_percent / 100 * ( array.min_temp - 25));
array.max_sys_voltage = sf.max( array.max_sys_voltage_1, array.max_sys_voltage_2 );
array.min_voltage = array.smallest_string * module.vmp * ( 1 + module.tc_vpmax_percent / 100 * ( array.max_temp - 25 ) );
array.pmp = array.num_of_modules * module.pmp;
array.voc = source.voc;
array.isc = module.isc * array.num_of_strings;
array.vmp = module.vmp * array.largest_string;
array.imp = module.imp * array.num_of_strings;
array.isc_adjusted = array.isc * 1.25;
array.vmp_adjusted = array.max_sys_voltage_2;
array.circuits_per_MPPT = Math.ceil( array.num_of_strings / inverter.mppt_channels );
array.combined_isc = source.isc * array.circuits_per_MPPT;
array.combined_isc_adjusted = module.isc * 1.25 * array.circuits_per_MPPT;
array.max_sys_voltage_2 = array.max_sys_voltage_2;
```

The maximum array voltage is must not exceed the maximum system voltage allowed by the module.

```
error_check['array_test_1'] = array.max_sys_voltage > module.max_system_v;
if(error_check[ 'array_test_1' ]){ report_error( 'Maximum system voltage exceeds the modules max system voltage.' );}
```

The maximum array voltage is must not exceed the maximum system voltage allowed by the building code.

```
error_check['array_test_2'] = array.max_sys_voltage > array.code_limit_max_voltage;
if(error_check[ 'array_test_1' ]){ report_error( 'Maximum system voltage exceeds the maximum voltage allows by code.' );}
```

The maximum array voltage is must not exceed the maximum system voltage allowed by the inverter.

```
error_check['array_test_3'] = array.max_sys_voltage > inverter.vmax;
if(error_check[ 'array_test_1' ]){ report_error( 'Maximum system voltage exceeds the inverter maximum voltage rating' );}
```

The minimum array voltage must be greater than the inverter minimum operating voltage.

```
error_check['array_test_4'] = array.min_voltage < inverter.voltage_range_min;
if(error_check[ 'array_test_1' ]){ report_error( 'Minimum Array Vmp is less than the inverter minimum operating voltage.' );}
```

The total array power must be less than 10,000W.

```
error_check.power_check_array = array.pmp > 10000;
if( error_check.power_check_array ){ report_error( 'Array voltage exceeds 10kW' );}
```

The combined DC short circuit current from the array must be less than the maximum allowed per inverter MPPT channel.

```
error_check.current_check_inverter = array.combined_isc > inverter.imax_channel;
if( error_check.current_check_inverter ){ report_error( 'PV output circuit maximum current exceeds the inverter maximum dc current per MPPT input.' );}
```

Inverter

If max_ac_ocpd is not provided by the manufacturer, it is calculated as follows:

AC_OCPD_max = max_ac_output_current * 1.25

The nominal_ac_output_power is selected from fields based on the user selected grid voltage. As an example, if the user selects 240 VAC, then:

nominal_ac_output_power = nominal_ac_output_power_240
max_ac_output_current = max_ac_ouput_current_240

```
inverter.AC_OCPD_max = sf.if( sf.not( inverter.max_ac_ocpd ), inverter.max_ac_output_current * 1.25, inverter.max_ac_ocpd );
inverter.nominal_ac_output_power = inverter['nominal_ac_output_power_'+inverter.grid_voltage];
inverter.max_ac_output_current = inverter['max_ac_ouput_current_'+inverter.grid_voltage];
```

Interconnection

At least one of the following checks must not fail:

- The sum of 125 percent of the inverter(s) output circuit current and the rating of the overcurrent device protecting the busbar exceeded the ampacity of the busbar.
- The sum of 125 percent of the inverter(s) output circuit current and the rating of the overcurrent device protecting the busbar exceeded 120 percent of the ampacity of the busbar.
- The sum of the ampere ratings of all overcurrent devices on panelboards exceeded the ampacity of the busbar.

```
interconnection.check_1 = ( ( interconnection.inverter_output_cur_sum * 1.25 ) + interconnection.supply_ocpd_rating ) > interconnection.bussbar_rating;
interconnection.check_2 = ( interconnection.inverter_output_cur_sum * 1.25 ) + interconnection.supply_ocpd_rating > interconnection.bussbar_rating * 1.2;
interconnection.check_3 = ( interconnection.inverter_ocpd_dev_sum + interconnection.load_breaker_total ) > interconnection.bussbar_rating;

error_check.interconnection_bus_pass = sf.and( interconnection.check_1, interconnection.check_2, interconnection.check_3 );
if( error_check.interconnection_bus_pass ){ report_error( 'The busbar is not compliant.' );}
```

The panel's main OCPD must not exceed the bussbar rating.

```
error_check.interconnection_check_4 = interconnection.supply_ocpd_rating > interconnection.bussbar_rating;
if( error_check.interconnection_check_4 ){ report_error( 'The rating of the overcurrent device protecting the busbar exceeds the rating of the busbar. ' );}
```

Conductor and conduit schedule

For string inverters, this is the circuit names:

- Exposed source circuit wiring: DC wires exposed on the roof.
- PV DC source circuits: DC wires in conduit.
- Inverter ac output circuit: AC circuits between the inverter and panel OCPD.

  var circuit_names = [
  'exposed source circuit wiring',
  'pv dc source circuits',
  'inverter ac output circuit',
  ];
  circuit_names.forEach(function(circuit_name){
  circuits[circuit_name] = {};
  });

The array temperature adder is found in NEC table 310.15(B)(3)(c), with module.array_offset_from_roof as "Distance Above Roof to Bottom of Conduit (in)".

```
circuits['exposed source circuit wiring'].temp_adder = sf.lookup( module.array_offset_from_roof, tables[1] );
```

The maximum current and voltage for the array DC circuits are equal to source.isc and source.voc.

```
circuits['exposed source circuit wiring'].max_current = array.combined_isc;
circuits['exposed source circuit wiring'].max_voltage = source.voc;
circuits['pv dc source circuits'].max_current         = array.combined_isc;
circuits['pv dc source circuits'].max_voltage         = source.voc;
```

The number of DC current carrying conductors is equal to twice the number of strings in the array (array.num_of_strings * 2).
Total conductors adds one more for the ground.

```
circuits['exposed source circuit wiring'].total_cc_conductors = ( array.num_of_strings * 2 );
circuits['exposed source circuit wiring'].total_conductors    = ( array.num_of_strings * 2 ) + 1;
circuits['pv dc source circuits'].total_cc_conductors         = ( array.num_of_strings * 2 );
circuits['pv dc source circuits'].total_conductors            = ( array.num_of_strings * 2 ) + 1;
```

The AC grid voltage is defined by system specifications (user input).

```
circuits['inverter ac output circuit'].max_voltage = inverter.grid_voltage;
```

The maximum AC output is defined by the inverter manufacturer specifications.

```
circuits['inverter ac output circuit'].max_current = inverter.max_ac_output_current;
```

AC conductors numbers are defined by the grid voltage.

```
var conductors_options = {
  '120V': ['ground','neutral','L1'],
  '240V': ['ground','neutral','L1','L2'],
  '208V': ['ground','neutral','L1','L2'],
  '277V': ['ground','neutral','L1'],
  '480V Wye': ['ground','neutral','L1','L2','L3'],
  '480V Delta': ['ground','L1','L2','L3'],
};
inverter.conductors = conductors_options[inverter.grid_voltage+'V'];
inverter.num_conductors = inverter.conductors.length;

circuits['inverter ac output circuit'].total_cc_conductors = inverter.num_conductors - 1;
circuits['inverter ac output circuit'].total_conductors = inverter.num_conductors;
```

For each circuit, calculate the following.

```
circuit_names.forEach(function(circuit_name, i){
  var circuit = circuits[circuit_name];
  circuit.id = i;



  circuit.power_type = sf.index( ['DC', 'DC', 'AC'], circuit.id );
  // If temperature adder is not defined, set it to 0 for use in further calculations.
  circuit.temp_adder = sf.if( circuit.temp_adder, circuit.temp_adder, 0 );
```

The array maximum temperature of the array is equal to the 2% maximum temperature at the install location, or nearest weather station.
For a state wide design, the largest maximum temperature for the state is used.
Rooftop array circuits also have a temperature adjustment defined above.

```
  circuit.max_conductor_temp = array.max_temp + circuit.temp_adder;
  circuit.temp_correction_factor = sf.lookup( circuit.max_conductor_temp, tables[2] );
  circuit.conductors_adj_factor = sf.lookup( circuit.total_cc_conductors , tables[3] );
```

There are three options to calculate the minimum required current:

1. circuit.max_current * 1.25;
2. circuit.max_current / (circuit.temp_correction_factor * circuit.conductors_adj_factor);
3. circuit.max_current * 1.25 * 1.25;

```
  circuit.min_req_cond_current_1 = circuit.max_current * 1.25;
  circuit.min_req_cond_current_2 = circuit.max_current / ( circuit.temp_correction_factor * circuit.conductors_adj_factor );
  circuit.min_req_cond_current_3 = circuit.max_current * 1.25 * 1.25;
```

For AC circuits, the maximum of 1 and 2 is used. For DC circuits, the maximum of 2 and 3 is used.

```
  circuit.min_req_cond_current    = sf.max( circuit.min_req_cond_current_1, circuit.min_req_cond_current_2 );
  circuit.min_req_OCPD_current_DC = sf.max( circuit.min_req_cond_current_2, circuit.min_req_cond_current_3  );
  circuit.min_req_OCPD_current = sf.if( circuit.power_type === 'DC', circuit.min_req_OCPD_current_DC,
circuit.min_req_cond_current_1);
```

For strings per MPP tracker of 2 or less, or for inverters with built in OCPD, additional DC OCPD is not required. The AC circuits do require OCPD at the panel.

```
  circuit.OCPD_required = sf.index( [false, false, true ], circuit.id );
  circuit.ocpd_type = sf.index( ['NA', 'PV Fuse', 'Circuit Breaker'], circuit.id );
```

Choose the OCPD that is greater or equal to the minimum required current.

```
  circuit.OCPD = sf.lookup( circuit.min_req_OCPD_current, tables[8], 0, true, true);
```

Choose the conductor with a current rating that is greater than the OCPD rating from NEC table 310.15(B)(16).
NEC chapter 9 table 8 provides more details on the conductor. For 'exposed source circuit wiring', 10 AWG wire is used as a best practice.

```
circuit.min_req_cond_current = sf.if( circuit.OCPD_required, circuit.OCPD, circuit.min_req_OCPD_current );
circuit.conductor_current = sf.lookup( circuit.min_req_cond_current, tables[4], 0, true);
circuit.conductor_size_min = sf.lookup( circuit.conductor_current, tables[4] );
if( circuit_name === 'exposed source circuit wiring' ){ circuit.conductor_size_min = '10'; }
circuit.conductor_strands = sf.lookup( circuit.conductor_size_min, tables[5], 2 );
circuit.conductor_diameter = sf.lookup( circuit.conductor_size_min, tables[5], 3 );
circuit.min_req_conduit_area_40 = circuit.total_conductors * ( 0.25 * PI() * circuit.conductor_diameter ^2 );
```

The NEC article 352 and 358 tables are used to find a conduit with a sufficent 40% fill rate to hold the total conductor size for all the conductors.

```
circuit.min_conduit_size_PVC_80 = sf.lookup( circuit.min_req_conduit_area_40, tables[6] );
circuit.min_conduit_size_EMT = sf.lookup( circuit.min_req_conduit_area_40, tables[7] );
```

Select further wire details based on code requirements and best practices.

Exposed source circuit wiring:

- Conductor: 'DC+/DC-, EGC'
- Location: 'Free air'
- Material: 'CU'
- Type: 'PV Wire, bare'
- Volt rating: 600
- Wet temp rating: 90
- Conduit type: 'NA'

PV DC source circuits:

- Conductor: 'DC+/DC-, EGC'
- Location: 'Conduit/Exterior'
- Material: 'CU'
- Type: 'THWN-2'
- Volt rating: 600
- Wet temp rating: 90
- Conduit type: 'Metallic'

Inverter ac output circuit:

- Conductor: 'L1/L2, N, EGC'
- Location: 'Conduit/Interior'
- Material: 'CU'
- Type: 'THWN-2'
- Volt rating: 600
- Wet temp rating: 90
- Conduit type: 'Metallic'

```
circuit.conductor = sf.index( ['DC+/DC-, EGC', 'DC+/DC-, EGC', 'L1/L2, N, EGC'], circuit.id );
circuit.location = sf.index( ['Free air', 'Conduit/Exterior', 'Conduit/Interior'], circuit.id );
circuit.material = 'CU';
circuit.type = sf.index( ['PV Wire, bare', 'THWN-2', 'THWN-2'], circuit.id );
circuit.volt_rating = 600;
circuit.wet_temp_rating = 90;
circuit.conduit_type = sf.index( ['NA', 'Metallic', 'Metallic'], circuit.id );



///////
// cleanup for display
if( ! circuit.OCPD_required ){
  circuit.ocpd_type = '-';
  circuit.OCPD = '-';
}
circuit.conductor_size_min = circuit.conductor_size_min + ', ' + circuit.conductor_size_min;
//////
```

});