For each of the enabling technologies (EH, ES, MPM) a set of tables and questions/notes for consideration has been compiled. The ambient energy considerations have been integrated into the EH section but of course these have knock-on implications for storage and power management functionalities.

- Energy Harvesting
    - Solar
    - Vibrational
    - Thermoelectric generators (TEG)
    - RF and Wireless Power Transfer (WPT)
- Energy Storage
- Micropower Management

1. Energy Harvesting

In this section we focus on the 4 most prevalent primary ambient energy source types.

1.1 Solar

Part number/type			*Suitable light sources*			*Technology Readiness Level (TRL)*	
Lighting level	**50 lux**	**100 lux**	**200 lux**	**350 lux**	**500 lux**	**10,000 Lux (outdoor)**	**Other (specify conditions)**
Power (uW/cm2)							
Temperature range							
Open circuit Voltage							
Voltage at MPP (per cell)							
Open circuit impedance?							
Any other notable characteristic?	**(e.g. DSSC (dye sensitized solar cells) are flexible)**						

Table 1: PV characterisation template

Questions/considerations:-

- PV parts are usually characterized by a family of V-I curves at different lighting (lux) levels. Ref. fig. 1 below for an example. They may also vary as a function of temperature and additional curves supplied for different ambients.
- Impedance matching schemes are often used to find and track the maximum power point (MPP). For most parts a good approximation to MPPT is around 74% of the open circuit voltage.
- Outdoor lighting is relatively straightforward and PV technology well established. However many applications only have access to indoor light which delivers only a small fraction of the power of outdoor light (e.g. 300lux delivers around 1-2% of normal outdoor lighting power). The performance of indoor PV panels varies substantially based on the indoor light source due to the difference in wavelength found (natural, incandescent, LED, fluorescent, etc.) and different PV technologies offer trade-offs in terms of performance versus ‘range’ of wavelengths at which decent power is generated. This is difficult to characterize but at least the strengths of a particular technology should be captured in its characterization (e.g. amorphous silicon covers a decent range of wavelengths).
- Cells can be added in series or parallel to create a suitable voltage range but this affects charge rates and MPP tracking.

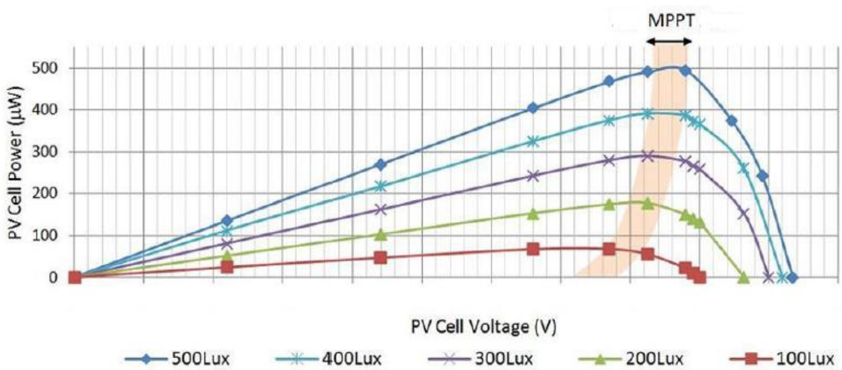

Fig. 1. Family of indoor PV cell V-I characteristics (current converted to power)

1.2 Vibrational

Part number/type			***Application suitability***		**e.g. machines, wearables.**	***Technology Readiness Level (TRL)***	
Resonant frequency (Hz)							**Comments**
Frequency range							
Acceleration	**50 mG**	**100 mG**	**250 mG**	**500 mG**	**1G**	**3G?**	
Amplitude	**(Enter suitable amplitude(s) for each acceleration)**						
Device power (uW)							
Voltage generated							
Device Dimensions							**Outline any significant variations**
Temperature range							
Power density (uW/cm3)							
Output Voltage at MPP							
Circuit impedance?							
‘Tunability’							

Table 2: Vibrational source characterisation template

Questions/considerations:-

- It is difficult to capture the myriad of combinations of frequency, vibration and amplitudes but where possible ambient energy conditions reflecting real life scenarios should be used. e.g. for wearables frequencies in the 1- 10s of Hz, for automotive 10s-100s of Hz, for vibrations from mains powered devices (such as motors) frequencies of 50/60Hz and their multiples.
- ***‘Frequency range’*** should be accompanied by a suitable explanation note, e.g. the range at which say >30% of the peak power is still available.
- There are different types of devices:- piezoelectric are typically high voltage, high impedance & higher resonant frequency; electromagnetic parts lower voltage, impedance and resonant frequency. Electrostatic are suitable for miniaturization and tunability of electro-mechanical conversion factors
- ***‘Tunability’*** refers to the extent to which resonant frequency can be reasonably adjusted. The resonant frequency of many devices can be tuned by adjusting form factor, weights, materials, etc. but the extent to which this can be reasonably manipulated would be very helpful to know (ability to fit into a typical application and manufacturability).
- Additional info on scalability of parts (minimum dimensions, how many parts could be connected together to increase power, etc.) should be supplied where possible.

1.3 Thermoelectric generators (TEG)

Part number/type						*Technology Readiness Level (TRL)*	
ΔT	**2K**	**5K**	**10K**	**20K**	**50K**	**‘other’**	**Comments**
Power (uW)							
Voltage generated							
Device Dimensions							
Power density (uW/cm3)							
Efficiency (if available)							
Thermal resistance	**°C/W**						
Suitable temperature range							
Seebeck co-efficient							
Resistance at 25°C							

Table 3: Thermoelectric source characterisation template

Questions/considerations:-

- Whilst most TEG devices give datasheets covering a broad temperature range the data for small temperature increments (<10°C) tends to be limited and the power generated very low.
- However this amount of power (10s of 10uW) can be useful for many IoT applications.
- Small temperature increments can be found in many applications, e.g. body heat from wearables, walls/windows within buildings, ground to air interfaces (soil monitoring).
- We expect to see many more MEMS scale TEG device emerge on the market to better avail of such ambient energies.
- Thermal resistance of the stand-alone device is often insufficient information. Metrology or simulation is needed to understand the thermal resistance of the part to which the TEG is connected (heatsink, housing, etc.) or to determine what size part is needed to create the desired temperature gradient.

1.4 RF/WPT (wireless power transfer)

Part number/type			***RF Power sources***			***Technology Readiness Level (TRL)***	
Frequency bands	***UHF (cellular, DTV, RFID)***				***mmWave***		
RF Power Level (dBm)	**-30 (indoor ambient)**	**-20 (multi-band ambient)**	**-15 to -10 (outdoor ambient**	**0 to 10 (RFID, phone call)**			
Rectenna bandwidth							
Power conversion efficiency, PCE (DC/RF)	**<10%**	**30%**	**50%**	**>80%**			
Antenna gain and polarization	Circular polarization, dual/all-polarization with RF/DC combining						
RF sensitivity (RF power level at which required DC voltage is achieved)							
DC Load Impedance at max PCE							
Any other notable characteristic?	**Antenna on flexible substrate, fully-integrated antenna on-chip/in-package**						

Questions/considerations:-

- For certain antenna designs, bandwidth and gain are not necessarily a figure of merit, as they are usually bottle-necked with the rectifier’s bandwidth. Although the gain is a deciding factor on harvested power, when reporting testing results the impact of the polarization angle needs to be considered (ambient RF energy harvesting).
- In a CMOS rectifier, is the achieved PCE dependent on a certain process (Si on Insulator, Si on Sapphire, etc…) or certain devices (Zero/Low voltage threshold transistors).
- Matching networks and antenna-rectifier co-design are highly dependent on the RF power levels, the frequency and load impedance; the impedance is highly non-linear. For example, a rectenna that could be tuned at 3+ GHz (at >1mW power levels) cannot necessarily be optimized to operate sub- 1 GHz.

2. Energy Storage

Energy storage plays a key role in ‘power IoT’ systems. In many cases the power source is simply a single use energy storage device such as a battery. In other instances the energy storage device is re-chargeable (e.g. micro-battery, supercap) and plays a critical role in the conversion of any excess ambient energies available. More frequently we shall see hybrid solutions whereby a single use battery provides a reliable power source whilst the EH source replenishes another energy storage that minimized battery depletion when ambient energy has been harvested and stored.

Part number/type		*Comments*
Technology Readiness Level (TRL)		
Storage Capacity (F/mAhr)		
Power delivery capability		
Dimensions		**(Also min thickness, is it flexible?)**
Voltage range		
Leakage current		**(This may need to be a graph as a function of voltage & time?)**
Number of cycles		
Temperature range		
Energy density (mAhr/mm3)		
Power density (uW/cm3)		
ESR (effective series resistance)		**(This may need to be a graph as a function of frequency?) (Overall impedance may also be useful for PMIC interfacing?)**
Scalability		**(Is it possible to put multiple parts in series &/or parallel + any related application notes)**
Temperature range		**Outline any significant variations as required, e.g. self discharge**
Likely usage		

Questions/considerations:-

- When filling out the template the primary function should be carefully considered, e.g. is it likely to be a single end use part or re-chargeable? Will the part only be re-charged when fully depleted or will it receive frequent charges from an ambient energy source
- Leakage current will vary depending on operational voltage, whether the part is in shallow or deep discharge mode will vary with time. A series of curves may be required and additional testing necessary to determine performance for a given application scenario.
- Scalability refers to the ability to connect multiple parts in series or parallel and also to the potential for the technology to be scaled as required (e.g. can capacity be doubled by doubling the area/volume of the part).

3. Micro-Power Management

This is typically provide by some type of PMIC (Power Management IC) with a number of ancillary circuits. In some cases, an IoT semiconductor device may have other functionalities embedded on chip or in a multi-chip module (e.g. microcontroller, transceiver, sensors).

Part number/type		*Comments*
Technology Readiness Level (TRL)		**Also outline if the MPM is discrete or IC, provide application notes, etc.**
Input Source		**AC (piezo? Magnetic? RF?) DC (solar? TEG? RF?) Both? Constraints on transducer output resistance/impedance?**
Type of converter		**Converter topology, type of MPPT, etc.**
Efficiency		
Quiescent current		
Input voltage range		**(Also min thickness, is it flexible?)**
Input frequency range		
Output voltage range		**(Also if regulated / not-regulated)**
Minimum input voltage after cold start		
Minimum input power after cold start		
Temperature range		
Cold start power source capability		
Minimum input voltage/power to perform cold start		
Digital interface capability		
Number/Type/Value of passive elements		
Maximum output power		
Optimization algorithms		
MPPT functionality		**If used - what kind of MPPT (digital, analog, OCV, etc.)**
Other functionalities		**(Specify whether embedded or ancillary circuit required)**

Questions/considerations:-

- ***Input source:*** The main aspect here to be considered to discriminate between different solutions is the type of target input source, i.e. is it AC or DC? If it is AC, what is the nature of its impedance, capacitive, inductive? And if DC for example, is it for high voltage (solar?) or low voltage (TEG, RF?), or what is its output resistance?
- ***Efficiency:*** Ideally a family of curves showing efficiency as a function of input and output voltage and load is required. As an alternative, efficiency in different operating points (conditions of energy source and of load) should be provided. An indication of maximum efficiency should be provided along with the related operational conditions.
- ***Quiescent current:*** Many wireless IoT devices spend most of their time in quiescent mode so their quiescent mode current can significantly impact battery life. This includes quiescent current of the PMIC along with sensors, microcontrollers, transceivers, etc. Quiescent current of the PMIC sets an asymptotic lower bound of the minimum input power required to operate.
- ***Input frequency range:*** In case of AC sources a suitable range of input frequencies should be provided.

- ***Minimum input voltage after cold start:*** In a hybrid system a battery can perhaps provide the minimum input voltage to cold start the system based on energy available from a transducer. Alternatively ambient energies can be accumulated and boosted, then connected to the load when a sufficient amount has been stored. The problem with this is that the ambient energy source may be sporadic and retreat to relatively low operating voltage levels for a given period. This could result in sporadic engaging and disengaging of the energy harvesting source to the load and affect continuity of supply. Also, in most MPM EH circuits, there is a combination of two constraints to determine the operability of the system: minimum input voltage and minimum input power, which must be both satisfied.
- ***Cold Start Power Source Capability:*** PMICs require a minimum amount of energy from a transducer (energy harvesting source) in order to cold start, e.g. due to in-rush current or to the need of charging initially internal nodes and storage. Often the critical point is to get the minimum voltage from a TEG to switch a first transistor. Same can happen with piezos and current. For many applications the ambient energies can be low and this can impede the ability of the transducer to deliver power. This is effectively a Boolean attribute. Consequently it would be useful to specify also the minimum input voltage/power to perform the cold start. Note that typically these values are slightly higher than minimum values required to operate the module.
- ***Digital interface capability:*** PMICs can play an important role in changing operational mode of other devices (sensors, actuators, micro-controllers, transceivers) based on energy available and application needs. For example it may be acceptable to change sensing interval temporarily to a longer period in the event of the energy source being almost depleted. Also specify if they are standard interfaces (SPI/I2C etc.) or custom control signals
- ***Number/Type/value of passive elements:*** For many commercial customers a valuable figure of merit is the need for ancillary passive elements (number/value of inductors/capacitors/resistors) in order to forecast the cost/area constraints. This also relates to any other functionalities considered.
- ***Maximum output power:*** An immediate item to understand if a particular MPM is suitable for a possible application is to know the maximum available output power in typical conditions
- ***Optimization algorithms:*** (If any). This can be an interesting element to judge the possible performances of the MPM circuit (e.g. MPP algorithm).
- ***Other functionalities:*** It should be clear what functionalities are embedded in the MPM (and whether discrete or IC) versus what needs to be added externally. Application circuits for ancillary circuits should be supplied.

4. Conclusions & Recommendations

The methodology devised herein when creating new ‘power IoT’ library parts (for energy harvesting, storage, micro-power management and their system integration) is a set of initial templates along with questions for consideration. This assists with enabling ‘apples versus apples’ comparisons of parts and aligning/interfacing with other components in building ‘power IoT’ solutions for various applications.

The rationale behind the creation of these templates was outlined along recommendations for future consideration.

JRA activity leaders have agreed to take ownership for implementing the use of these templates & questions for JRAs and TAs as well as enhancing them based on learnings on both activities.

It is well understood that it will not be possible to capture all attributes but at least provision for them should be made.

Templates cannot possibly cover all scenarios so some pragmatism is required based on the likely usage of the parts in a given set of scenarios (e.g. type of indoor lighting available, frequency, acceleration and amplitude of vibrational frequencies). Also provision is made for addition of valuable information regarding unique feature sets/capabilities and their suitability for various applications.