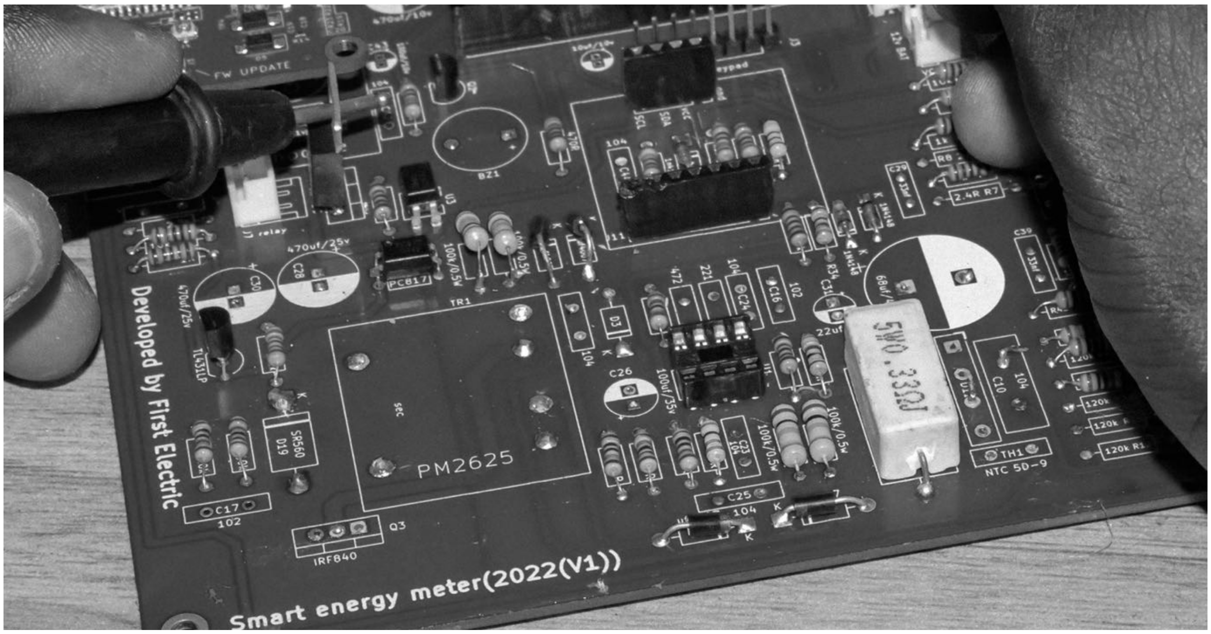
GSM SMART METER: OPEN-SOURCE DESIGN AND IMPLEMENTATION

"Solar Energy Developers require a transparent and affordable way to bill customers for electricity consumed".



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So why is this a big deal…

According to a report published by the BCG and AllOn, 85million (43%) Nigerians do not have access to grid-connected electricity. This represents about 15 million households and makes Nigeria the country with the largest energy access deficit in the world.
At the current electrification rate, leveraging conventional power solutions alone, ~30% of Nigeria's population will still be without electricity by 2030; resulting in a failure to achieve the governments ambitions of ensuring access to sustainable and reliable energy for the whole population (in line with UN SDG 7) and Nigeria's Energy Transition Plan.

One of the key barriers to rapid expansion and investment in the energy access market has been the affordability of solar solutions. With the average per capita income in Nigeria of $2,000, buying solar equipment capable of supporting Productive Use Equipment (PUE) is out of reach for most citizens.

To address this affordability challenge, a few solar developers have rolled out some PayGo solutions which offer periodic access to solar equipment with the use of prepaid tokens. However, most of these PayGo solutions charge a fixed fee for a period without reference to the actual energy consumption of the users. This creates misalignment between users and solar energy providers. Mainstream meters such as Stemaco and SPARKMETER better cater to large developers for mini grid applications where many meters are to be deployed in one site. Smaller scale developers require more affordable, scalable prepaid meters that allow customers pay per kWh for only what they consume. These were the reasons that initiated our research into an affordable GSM Smart Meter project as it creates alignment between customers and Solar developers. We couldn't find a suitable meter that met our needs, so we put in an application to develop one and share it with the rest of the world ☺

Who are we?

First Electric was founded in May 2019 with a mission to provide sustainable electricity solutions to customers in both rural and urban communities. We started our operations by providing Solar Home Systems (SHS) through outright purchase. While this was a step in the right direction because it eliminated the use of diesel and petrol generators which cause air and sound pollution, its reach was limited due to the significant capital cost for these solar solutions. To overcome this challenge, we rolled out a lease to own model which initially proved to allow better reach. However, that model was found to be unsustainable due to the significant rate of customer default payment and the requirement to provide warranty periods more than what was provided by the equipment OEMs which posed a significant risk to the company.

In 2022, First Electric embarked on this research project funded by EnAccess to develop an open-source pre-paid smart energy meter with customizable API for easy web integration for online top up. This meter is compatible with both CICADA WiFi and GSM modules for increased connectivity options.

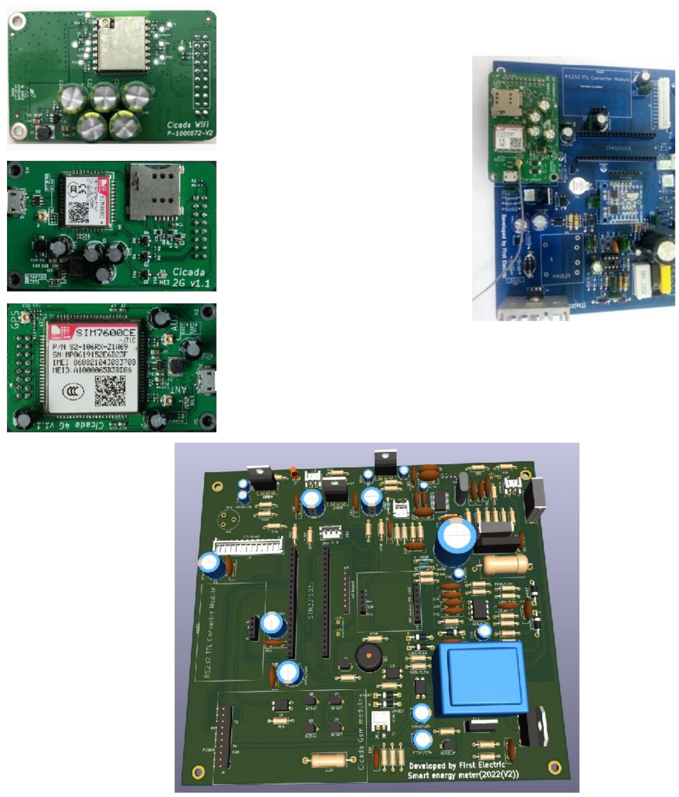

Figure 1: PCB of Meter + CICADA Modules

Smart Meter -Hardware & Firmware Design

The implementation of the smart GSM meter was done in 3 key stages as highlighted below; you can get more details following the embedded links.

- PCB Design and Enclosure design considerations
- Firmware, Web interface Development & API integration
- Calibration/testing on test bench

PCB and Enclosure Design Considerations

PCB design stage was very critical to the proper functioning of the smart meter. The main circuits of the PCB captured the following functions.

- Measurement.
- Display.
- Communication.
- STS token.
- Non-volatile memory.
- Microcontroller/coding platform.

Measurement	The measurement of metering parameters such as voltage, current, and energy was done using an AFE (Analog Front End) chip which guarantees a measurement accuracy of 0.5%, the current sampling method implemented is a current transformer (CT), while voltage divider was used to sample voltage as specified in the manufacturer's datasheet. An AFE chip was used due to its measurement accuracy over a wide measuring range and its suitability to meet the necessary features required for a single-phase meter as stated in the relevant IEC specification for meter development
Display:	The display of the meter was implemented on a 16x2 LCD screen which displays necessary

	metering parameters such as voltage, current, power factor, power, energy, credit. The information on the LCD scrolls every 10sec as required.
Communication:	The communication implemented hardware wise features Cicada GSM module, however the communication implemented from a software standpoint is MQTT (Message Queuing Telegraphy Transport), this enables user top-up via the web platform created and also view metering historic parameters via Thingsboard API.
STS **"Like"** token:	Manual STS token generation was implemented to enable users topup manually via keypad in event of network failure or another relating occurrence.
Non-volatile memory:	An external EEPROM (Electrically Erasable Programmable Memory) was used to enable vital data saving, also the EEPROM used promises a data retention of 100years with over 5,000 locations readable and writable 1,000,000 times.
Microcontroller/coding platform:	The microcontroller used is STM32f103ccu8, the code was written on Arduino IDE (Integrated Development Environment) and uploaded to the microcontroller via a USB to TTL converter module.

Meter Enclosure design was done to house all the PCB and provide a good level of protection. Image below is the 3D meter enclosure.

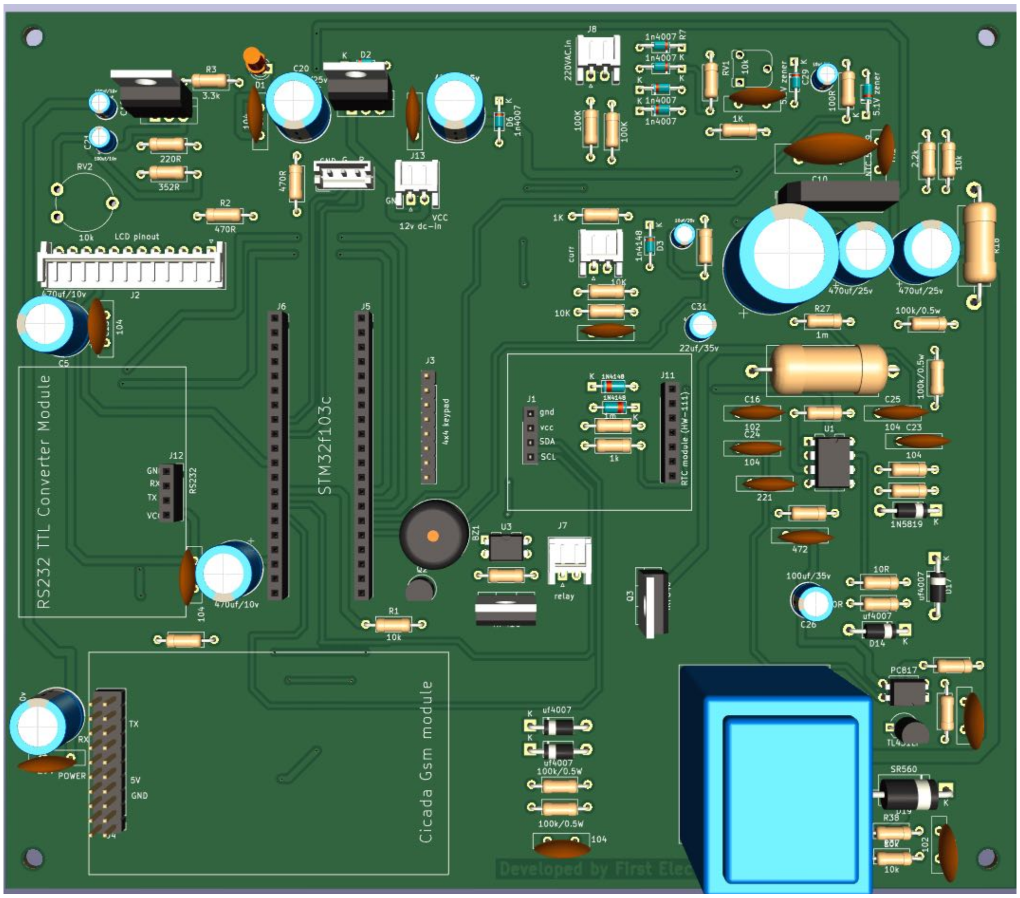

Figure 2: PCB Design

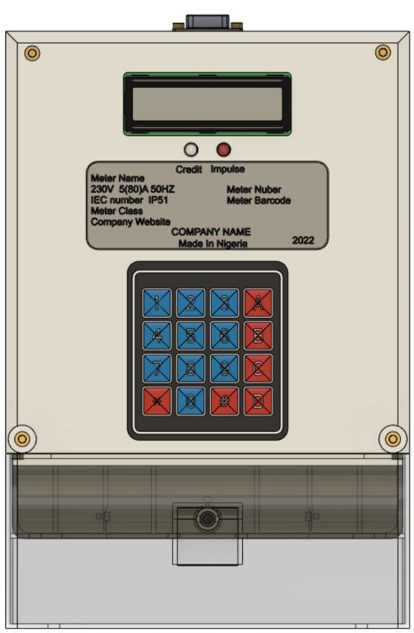

Figure 3: 3D Enclosure Design

Firmware, Web interface Development & API integration

The code was written in Arduino IDE using C++, while the web front end was written majorly in HTML and CSS while the back end was written majorly in PHP. Links to all these codes are [here].

Thingsboard API was used to view meter parameters such as energy, credit. Image of STS token generation, Paystack payment API, meter connection status and topup status. Thingsboard parameters logging is shown below.

Calibration & Testing on Test Bench

The calibration/testing is an essential stage of the meter design and implementation, and it was done via a test bench, the testing was done across different current, voltage, power factor. Image is shown below:

Figure 4:Testing at 5Amps

Figure 5: Testing at 30Amps

Figure 6: Testing at 60Amps.

Figure 7:Testing at 80Amps.

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The meter was designed and calibrated to achieve the specifications below.

Table 1: Meter Datasheet

S. NO.	DESCRIPTION	UNITS	SPECIFICATIONS
1	Type of meter		Single phase two wire
2	Accuracy Class of the meter		Class 1
3	Ib & Imax	A	5(80)
4	Operating Voltage	V	230
5	Operating Frequency	Hz	50
6	Power Consumption		2watts
7	Starting Current	mA	50
8	Short time over current	A	1000
9	Rated impulse withstand voltage	KV	1.5 (CAT II)
10	Resistance to heat and fire (As per specification		Fire retardant material was used in manufacturing the exterior casing
11	Degree of protection		IP51
12	Accuracy requirements (As per IEC 62053-21/22		Class 1
13	Power factor range		Zero lag to Zero.
14	Energy measurement		Fundamental energy + Energy due to Harmonics
15	Connection Diagram for system on terminal cover	Yes/No	Yes
16	Self-diagnostic feature		(i) Time and calendar. (ii) Real Time Clock. (iii) RTC battery. Non-Volatile Memory.
17	Initial start-up of meter (meter shall be fully functional within 5 sec after reference voltage is applied to the meter terminals)		Yes
18	Terminal block a) Depth of the Terminal holes. b) Internal diameter of terminal holes c) Clearance between adjacent terminals	Mm Mm Mm	9.5mm (minimum). 25 mm.
19	Communication capabilities as per clause 4.31		RS485
20	Immunity against HV ESD as defined in Cl. 4.32.2		(CBM) charged body model 2000V
21	DC Immunity as defined in Cl. 4.33		
22	Grade of material for a) Meter base. b) Meter cove. c) Terminal block.		Epoxy

	d) Terminal cover		
23	Tamper counts		yes
24	Recording forward energy in all conditions as per annexure I (Including current/potential reversal)	Yes/No	yes
25	Makes of all components used in the meter.	Yes/No	
26	Non-Volatile memory (Retention period)		100 years
27	Measuring elements used in the meter		CT
28	Power supply to circuit in case of supply failure		Battery
29	Display of measured values (As per specification –clause 5.8)	Yes/No	Yes
30	LCD display (Type and viewing angle)		16x2 LCD display
31	Pulse rate	Imp/kWh,Imp/kVArh	1000
32	Name plate marking	Yes/No	Yes

Three sample prototype meters were manufactured as required by the Nigerian Electricity Management Services Agency (NEMSA). These meters were calibrated at a 3rd Party test bench then tested in the Nigerian Electricity Management Services Agency (NEMSA) Metering Test Station (MTS) and the results for accuracy obtained are presented below. Tested meters: MT100, MT50 and MT25

MT100	MT50	MT25
		

Figure 8: Prototype Meters

MT100

Test point (%)	Voltage supplied (V)	Actual voltage (V)	Current supplied (A)	Actual current (A)	Expected power (W)	Actual power (W)	Error (%)
Imax 1.0	239.869	240	79.9683	79.96	19085.1	19190.4	-0.2752
Imax 0.5L	240.002	240	80.0044	80	9522.3	9600	0.191
1200 (1.0)	240.012	240	59.9996	59.99	14237.1	14397.6	0.442
1200	240.116	240	60.0088	60.02	7156.7	7202.4	0.0364
(0.5L)	240.018	240	30.0005	30.01	7194.11	7202.4	0.1744
(600 (0.5L)	240.015	240	30.0007	29.98	3598.5	3597.6	0.0154
(100 (1.0)	240.015	240	5.0063	5	1199.91	1200	-0.0602
100 (0.5L)	240.141	240	5.0033	5	602.67	600	-0.0475
5 (1.0)	0	0	0	0	0	0	0
5 (0.5L)	0	0	0	0	0	0	0

Table 2: Accuracy result or meter MT100

MT50

Test point (%)	Voltage supplied (V)	Actual voltage (V)	Current supplied (A)	Actual current (A)	Expected power (W)	Actual power (W)	Error (%)
Imax 1.0	240.008	240	79.995	79.74	19111.03	19137.6	0.4149
Imax 0.5L	240.19	240	80.2	79.94	9633.12	9592.8	-0.4011
1200 (1.0)	240.003	240	60.0051	59.91	14362.01	14378.4	0.0199
1200	239.99	240	59.9019	59.84	7307.49	7180.8	0.2463
(0.5L)	240.001	240	30.00014	29.97	7167.161	7192.8	0.038
(600 (0.5L)	240.19	240	30.00016	29.27	3601 5	3512.4	0.824
(100 (1.0)	239.998	240	5.00011	4.97	1190.211	1192.8	-0.0874

100 (0.5L)	240.027	240	5.00001	5.01	602.7	601.2	0.0351
5 (1.0)	0	0	0	0	0	0	0
5 (0.5L)	0	0	0	0	0	0	0

Table 3: Accuracy result or meter MT50

MT25

Test point (%)	Voltage supplied (V)	Actual voltage (V)	Current supplied (A)	Actual current (A)	Expected power (W)	Actual power (W)	Error (%)
Imax 1.0	240.062	240.8	80.0008	79.61	19151.99	19170.09	-0.5233
Imax 0.5L	240.135	240.8	80.0002	79.66	9621.6	9591.064	-0.3491
1200 (1.0)	240.003	240.9	60.0075	59.73	14382.55	14388 96	-0.1144
1200	239.863	240.9	59.9754	59.73	7111.8	7194.479	0.5069
(0.5L)	239.993	240.9	30	29.85	7192.41	7190.865	0.0542
(600 (0.5L)	239.999	241	29.9999	29.82	3612.74	3593.31	0.3466
(100 (1.0)	240.032	241	5.0064	4.99	1196.21	1202.59	0.2996
100 (0.5L)	240.039	241.1	5.00036	4.96	613.66	597.928	-0.0689
5 (1.0)	0	0	0	0	0	0	0
5 (0.5L)	0	0	0	0	0	0	0

Table 4: Accuracy result or meter MT50

Further details including source code, schematics, and manufacturing files can be found in the EnAccess github repository

Field Installation

Following successful testing and calibration of the meter, it was time to observe how the meter performed on the field. This involved putting the meter to use in the field. First Electric approached a local Shawarma shop in Ajah, Lagos, who mainly used petrol generator to provide electricity. We installed a 4kWp Solar Array with a 5kW Inverter and 5kWh battery storage which was sufficient to provide enough electricity for lighting and grilling.

The installation of the meter was relatively straightforward with input power cables going in at the right side of the meter and output cables to the load going out of the meter. We also installed a 32A overload output breaker for protection.

Figure 9: Meter installation in a shawarma sales shop.

Once powered up the meter LCD turns on, but power was not supplied to the load. Customer needed to recharge the meter to be able to use enjoy the solar electricity. The meter recharged and power supply to the load was activated. The customer was very pleased with the result as she was initially skeptical that solar would be able to power her grilling machine.

Figure 10: Close up image of meter powered on

The customer now enjoys a noise-free and smoke free environment to prepare her delicious "solar" shawarma. More importantly, she now makes more profit as her petrol and generator maintenance expenses are now eliminated.

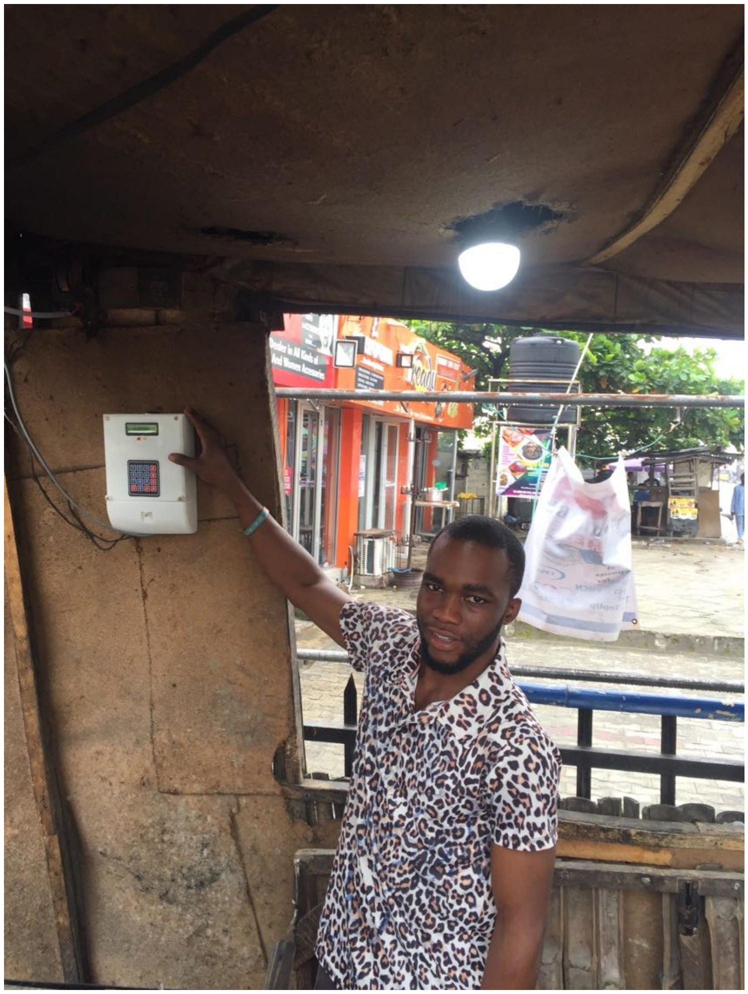

Figure 11: Image of meter with satisfied customer

Impact

Deploying Solar solutions using Energy as a Service has the potential to catalyze adoption of sustainable energy solutions. This is because reduces the financial barrier to adoption by making it more affordable. This Smart Meter is a key component that guarantees revenue assurance thereby giving developers and investors the confidence to make investment in deploying solar solutions.

For us at First Electric we believe deploying Energy as a Service with the use of a smart meter, we should be able to reach about 3125 businesses in the next few years.
Assuming each business has a daily energy consumption of 6kWh that equates to an annual energy consumption of 2,190kWh per business. Which is equivalent to

6,845,750kWh for all 3125 businesses. This equates to roughly 4,800 MT CO2eq. for each 3125 households reached. According to https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.

Lessons Learnt

During the execution of the project, we encountered several challenges some of which will be briefly highlighted here.

Unavailability of Own Test Bench: A key step in the meter design involves calibration of the meter. This was a little challenging as we did not own a test bench. We had to write to several labs that would give permission for us to use their test bench for meter calibration. This resulted in some delays to the project.

Supply Chain: Some key components such as the AFE chip were not available locally and had to be sourced from China, this resulted in some delays

Conclusion

This research project sort out to solve a problem that affects most solar developers in the industry. With the support of EnAccess we have been able to develop an inexpensive Smart Meter design which meets IEC and key elements of the local regulations. We are very pleased to have embarked on this and we look forward to commercially rolling out Energy as a Service Solutions using these meter designs. We also look forward to collaborating with other solar developers and stake holders to achieve similar objectives. For more information, please contact us via email info@firstelectricco.com

Other details

Bill of Materials

The following table is a rough breakdown of the costs and quantities of materials used in the project.

Components	QTY	Unit Price (USD)	Total Price (USD)
Stm32f103	1	$2.48	$2.48
Uc3843	1	$0.06	$0.06
4x4 keypad	1	$0.22	$0.22
12pinLCD connector	1	$0.01	$0.01
Cicada GSM module	1	$0.00	$0.00
Rs232 TTL converter module	1	$0.25	$0.25
Buzzer	1	$0.01	$0.01
RTC module (HW-111)	1	$0.32	$0.32
Bc547	5	$0.01	$0.03
L7805	1	$0.08	$0.08
3 Pin Connector	1	$0.01	$0.01
2pin connector	4	$0.01	$0.05
Capacitor (0.1uf multi-layer)	14	$0.00	$0.02
Capacitor(470uf/10v)	4	$0.03	$0.11
Capacitor(470uf/25v)	3	$0.03	$0.09
Capacitor(100uf/35v)	4	$0.03	$0.11
Capacitor(2.2uf/35v)	1	$0.03	$0.03
Capacitor(68uf/500v)	1	$0.22	$0.22
Resistor (1k, 1/4 watts)	8	$0.00	$0.03
Resistor (10k 1/4watts)	15	$0.00	$0.05
Resistor(470R,1/4watts)	3	$0.00	$0.01
Resistor (5.6k 1/4watts)	1	$0.00	$0.00
Resistor (352R, 1/4watts)	1	$0.00	$0.00
Resistor (2.2k, 1/4watts)	2	$0.00	$0.01
Resistor (0.47R 5watts)	1	$0.01	$0.01
Resistor (1M 1/4watts)	2	$0.00	$0.01
Resistor (variable(preset))	1	$0.02	$0.02
Diode(1n4007)	6	$0.01	$0.03
Diode(1n5819)	1	$0.02	$0.02
Diode(uf4007)	4	$0.02	$0.07
Diode (MBR2010)	1	$0.03	$0.03
Diode((KBL-410) bridge rectifier diode)	1	$0.10	$0.10
Pc817	3	$0.03	$0.09
Female header pin (1 roll)	1	$0.11	$0.11
Tl431	1	$0.01	$0.01
Ferrite core transformer (PQ2625)	1	$3.69	$3.69
Irf460 Mosfet	1	$0.08	$0.08
Capacitor (472) ceramic	1	$0.01	$0.01

Capacitor(103) ceramic	1	$0.01	$0.01
Capacitor(102) ceramic	3	$0.01	$0.02
Capacitor(221) ceramic	1	$0.01	$0.01
5.1v zener	2	$0.01	$0.02
Capacitor(104) MKP	1	$0.01	$0.01
Current transformer (100amps)	1	$2.02	$2.02
16x2 LCD	1	$1.04	$1.04
Magnetic latching relay	1	$2.07	$2.07
333	4	$0.01	$0.03
Atm90e26	1	$0.57	$0.57
120k	1	$0.00	$0.00
L7805	1	$0.07	$0.07
Lm350	2	$0.14	$0.29
LED	3	$0.00	$0.00
10k	7	$0.00	$0.02
100k(0.5 watt)	4	$0.00	$0.02
Diode(1n4148)	2	$0.02	$0.04
Resistor(10R 1/4watts)	2	$0.00	$0.01
Resistor (22R 1/4watts)	1	$0.00	$0.00
100k(1/4 watt)	7	$0.00	$0.02
Resistor(220R 1/4watts)	2	$0.00	$0.01
Resistor(2.4R 1/4watts)	2	$0.00	$0.01
TOTAL			$14.74