PROJECT 2 REPORT:
ENERGY ANALYSIS & OPTIMIZATION

INTRODUCTION

The aim of the project is to build an energy model for a voltmeter build using FRDM-KL25Z board , capable of sampling the supply voltage and flashing the appropriate LED color corresponding to the range of voltage in which the measured supply voltage falls under, at an interval for every 500ms.The ADC conversion for measuring supply voltage is performed in an ISR triggered by a low-power timer. The system is then analyzed and optimized for energy/power consumption using the energy model obtained. The following color scheme is used for LED flashing based on the measured supply voltage:

Vmin	Vmax	Flash Color
3.0 V	n/a	Blue
2.6 V	3.0 V	Magenta
2.2 V	2.6 V	Green
1.7 V	2.2 V	Red

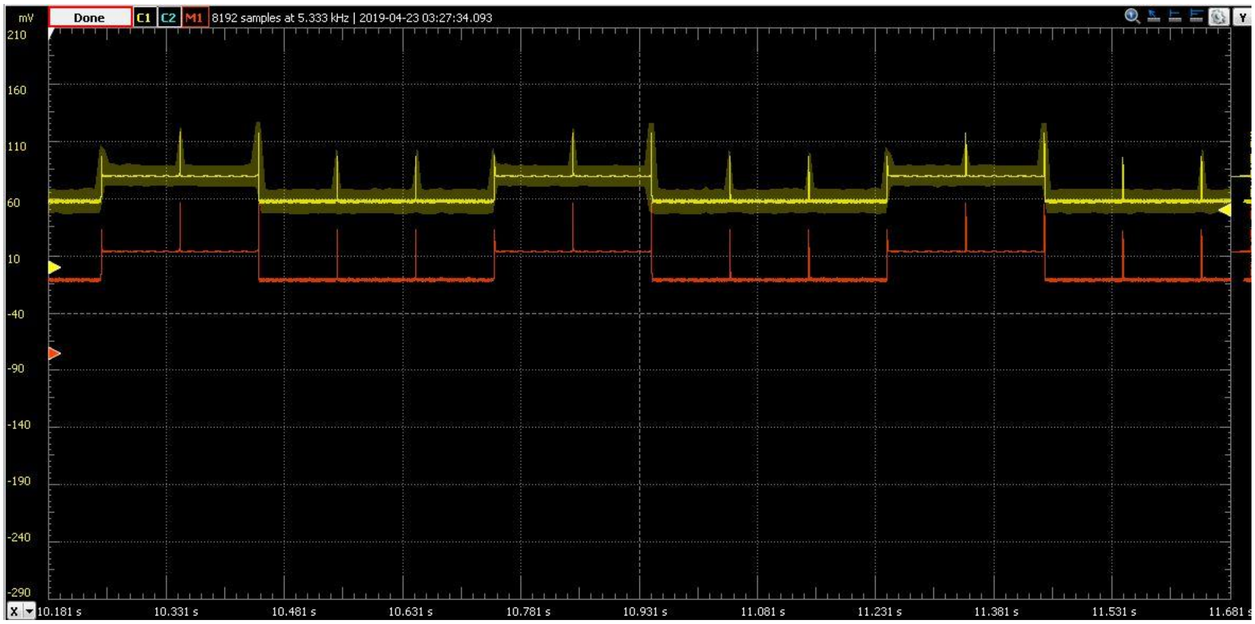
STARTER ENERGY MODEL

The following energy model was obtained for the starter code:

State	Current	Voltage	Time (duration per event)	Frequency(events per second)	Power	Duty cycle	Average power	Fraction of total average power
LED On,MCU running	5.12	3.3	1.158	4	16.896	0.004632	0.078262272	0.017003466
LED Off, MCU Running	2.76	3.3	1.158	6	9.108	0.006948	0.063282384	0.013748897
LED On,MCU sleeping	2.87	3.3	196.64	2	9.471	0.39328	3.72475488	0.809250003
LED Off, MCU Sleeping	0.378	3.3	295.184	2	1.2474	0.590368	0.736425043	0.159997634
					Total average power		4.602724579	

We can observe from the energy model greater fraction of the total average power is accounted by the LED on, MCU sleeping state of the system, so the first optimization would be aimed at reducing the power consumed by this state.

The following screenshot was taken with AD 2 for starter code:



OPTIMIZATION 1

The aim of this optimization is to reduce the amount of average power consumed by the LED On, MCU sleeping state based on the conclusion made from the starter energy model. This can be achieved by reducing the amount of time for which the LED will be On by reducing the LPTMR interrupt frequency and by turning off the LED immediately in the next interrupt after sampling the supply voltage. It is also made sure that even after implementing the optimization the system samples the supply voltage and flashes the LED at an interval of 500ms. The resistor used for this optimization is 10 Ω.

ATTEMPT 1

The system is configured to generate LPTMR interrupt at a frequency of 250 Hz (Time period of 4ms) in this attempt. The following energy model was obtained:

State	Current	Voltage	Time (duration per event)	Frequency(events per second)	Power	Duty cycle	Average power	Fraction of total average power
LED On,MCU running	4.05	3.3	0.672	2	13.365	0.001344	0.01796256	0.007624926
LED Off, MCU Running	1.75	3.3	0.895	250	5.775	0.22375	1.29215625	0.54850733
LED On,MCU sleeping	2.81	3.3	3.991	2	9.273	0.007982	0.074017086	0.031419508
LED Off, MCU Sleeping	0.389	3.3	378.45	2	1.2837	0.7569	0.97163253	0.412448235
					Total average power		2.355768426	

We can observe from the energy model that the contribution made by the LED On, MCU Sleeping state has reduced considerably and the total average power obtained is 2.335 mW.

ATTEMPT 2

The system is configured to generate LPTMR interrupt at a frequency of 100 Hz (Time period of 10ms) in this attempt. The following energy model was obtained:

State	Current	Voltage	Time (duration per event)	Frequency(events per second)	Power	Duty cycle	Average power	Fraction of total average power
LED On,MCU running	5.08	3.3	0.643	2	16.764	0.001286	0.021558504	0.010247167
LED Off, MCU Running	2.49	3.3	0.779	100	8.217	0.0779	0.6401043	0.304253755
LED On,MCU sleeping	2.81	3.3	9.943	2	9.273	0.019886	0.184402878	0.087650197
LED Off, MCU Sleeping	0.391	3.3	487.4	2	1.2903	0.9748	1.25778444	0.59784888
					Total average power		2.103850122	

We can observe from the energy model that the contribution made by the LED On, MCU Sleeping state has reduced but not to the extent by which it has reduced in the previous attempt, but the total average power has reduced even further to 2.103 mW as compared to the previous attempt. This can be attributed to decrease in the frequency of occurrence of LED off, MCU Running state s for interrupt frequency of 100 Hz as compared to the previous attempt. Hence this optimization was selected over the previous attempt since the total average power is less. The following changes were made in the code:

```
void LPTimer_IRQHandler(void) {
  float v_rail;
  static uint8_t n=LED_PERIOD;

  PTE->PSOR = MASK(DEBUG_RUNNING_POS);
  LPTMR0->CSR |= LPTMR_CSR_TCF_MASK;

  n--;
  if (n==LED_DURATION) {
    v_rail = Measure_VRef();
    Light_LEDs(v_rail);
  }
  else if(n==LED_DURATION-1)
  {
    Control_RGB_LEDs(0,0,0);
  }
  else if (n==0) {
    n = LED_PERIOD;
  };
}
```

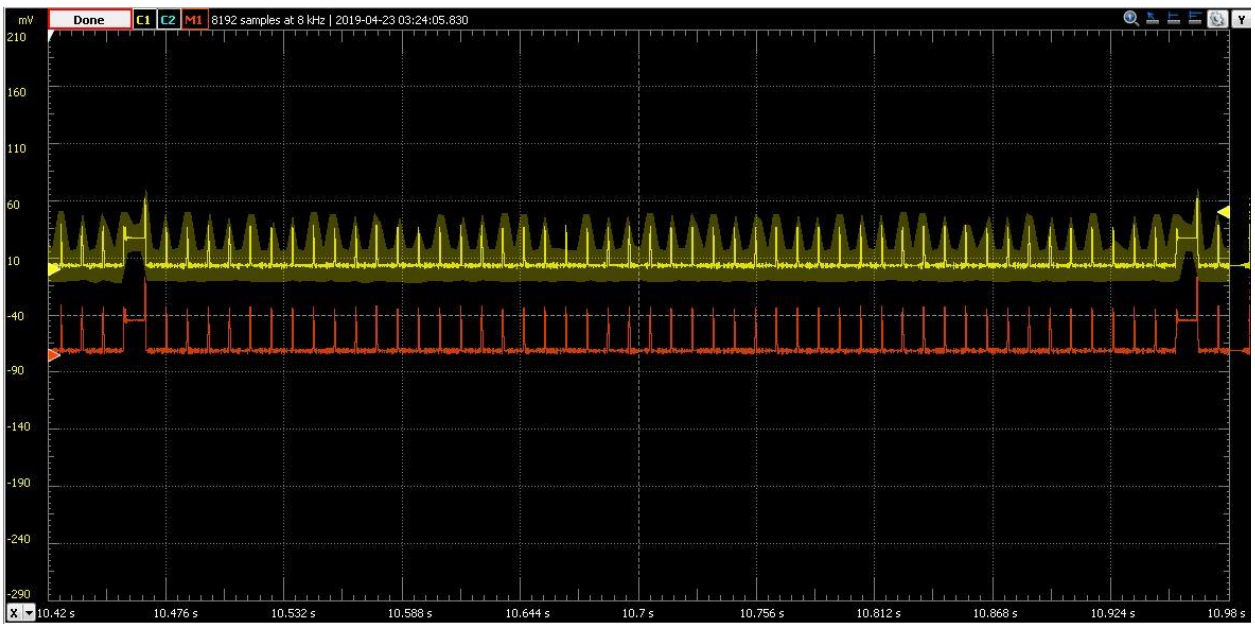
```c
void Init_LPTMR(void) {
  SIM->SCGC5 |=  SIM_SCGC5_LPTMR_MASK;

  // Configure LPTMR
  // select 1 kHz LPO clock with prescale factor 0, dividing clock by 2
  // resulting in 500 Hz clock
  LPTMR0->PSR = LPTMR_PSR_PCS(1) | LPTMR_PSR_PRESCALE(0);
  LPTMR0->CSR = LPTMR_CSR_TIE_MASK;
  LPTMR0->CMR = 4; // Generate interrupt every 5 clock ticks or 10 ms

  // Configure NVIC
  NVIC_SetPriority(LPTimer_IRQn, 3);
  NVIC_ClearPendingIRQ(LPTimer_IRQn);
  NVIC_EnableIRQ(LPTimer_IRQn);

}
```

The following screenshot was taken with AD 2 for this optimization:



OPTIMIZATION 2

This optimization is aimed at configuring the MCU for low power stop mode and low power run mode. It is aimed at reducing the contribution of LED off, MCU Sleeping state to the total average power.

ATTEMPT 1

In this attempt the MCU is configured to operate in LLS(Low leakage stop mode) and VLPR(Very low power run mode). The following energy model was obtained:

State	Current	Voltage	Time (duration per event)	Frequency(events per second)	Power	Duty cycle	Average power	Fraction of total average power
LED On,MCU running	2.97	3.3	1.1	2	9.801	0.0022	0.0215622	0.027230846
LED Off, MCU Running	0.846	3.3	1.919	100	2.7918	0.1919	0.53574642	0.676592742
LED On,MCU sleeping	2.205	3.3	9.838	2	7.2765	0.019676	0.143172414	0.180812064
LED Off, MCU Sleeping	0.035	3.3	395.45	2	0.1155	0.7909	0.09134895	0.115364348
					Total average power		0.791829984	

We can observe from the energy model that contribution made by the LED off, MCU Sleeping state has reduced and a total average power of 0.792 mW was obtained.

ATTEMPT 2

In this attempt the MCU is configured to operate in VLPS(Very low power stop mode) and VLPR(Very low power run mode). The following energy model was obtained:

State	Current	Voltage	Time (duration per event)	Frequency(events per second)	Power	Duty cycle	Average power	Fraction of total average power
LED On,MCU running	3.61	3.3	0.829	2	11.913	0.001658	0.019751754	0.027645919
LED Off, MCU Running	1.142	3.3	1.317	100	3.7686	0.1317	0.49632462	0.694690209
LED On,MCU sleeping	2.126	3.3	9.943	2	7.0158	0.019886	0.139516199	0.195276505
LED Off, MCU Sleeping	0.021	3.3	424.69	2	0.0693	0.84938	0.058862034	0.082387367
					Total average power		0.714454607	

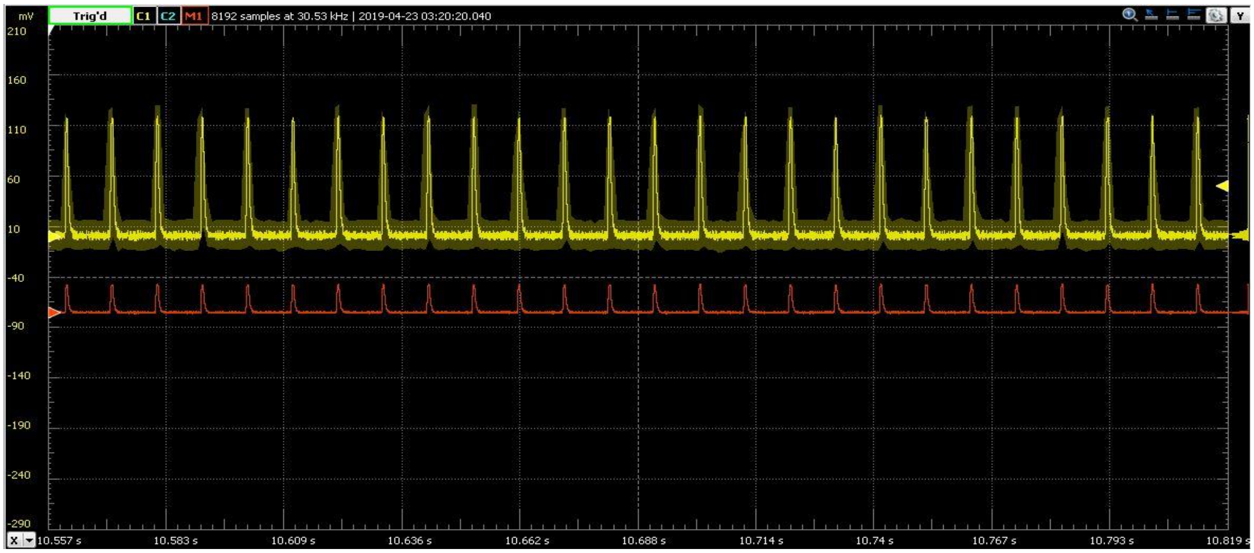
We can observe from the energy model that contribution made by the LED off, MCU Sleeping state has reduced considerably as compared to the previous attempt and a total average power of 0.714 mW less than that for the previous attempt was obtained. Hence this configuration is selected over the previous attempt. The following change was made in the code:

```
    // Allow LPTMR0 to wake LLWU
    LLWU->ME |= LLWU_ME_WUME0_MASK;
    SMC->PMCTRL = 0x42U;
    SCB->SCR |= SCB_SCR_SLEEPDEEP_Msk;


    Init_LPTMR();
    Start_LPTMR();
```

Here the MCU is configured to work in VLPS and VLPR mode by writing to SMC->PMCTRL register.

The following screenshot was taken with AD 2 for this optimization:



OPTIMIZATION 3

This optimization is aimed at operating the MCU in clock setup with better power consumption. The MCU is currently configured to operate with an external clock signal which results in greater time and power consumption while making up from the sleep mode. So the MCU was configured to operate with an internal clock signal resulting in lesser time and power consumption while waking up from sleep mode. The MCU was configured to operate with an internal clock of frequency of 20.97152 MHz. The following energy model was obtained:

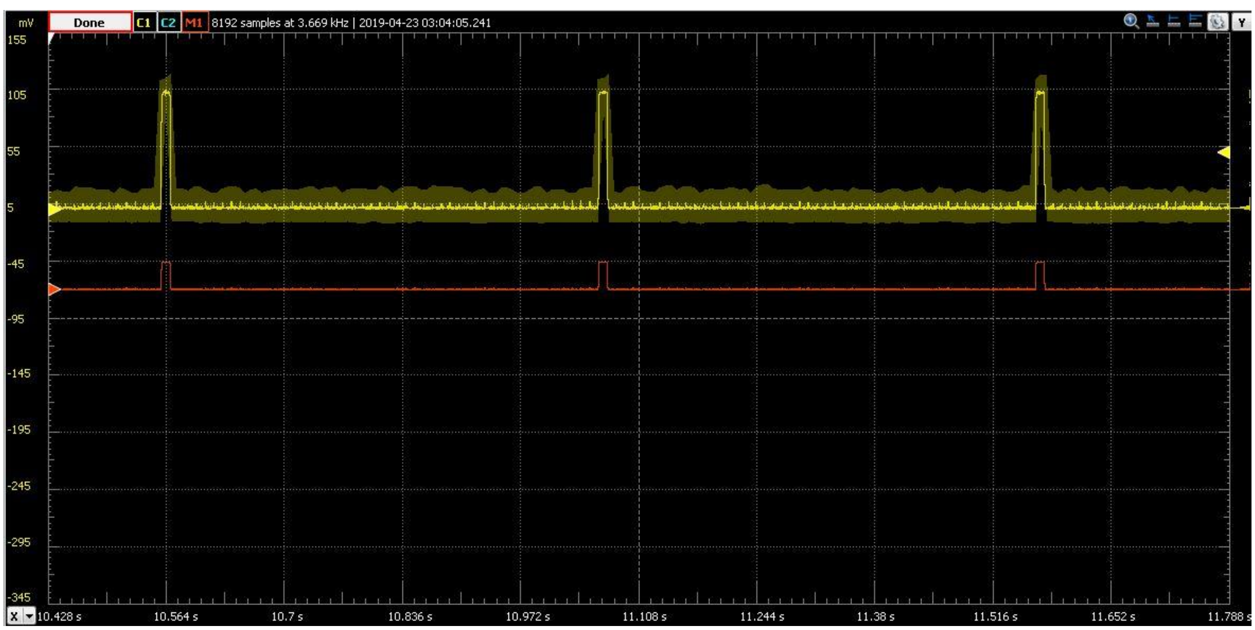
State	Current	Voltage	Time (duration per event)	Frequency(events per second)	Power	Duty cycle	Average power	Fraction of total average power
LED On,MCU running	2.17	3.3	0.047	2	7.161	0.000094	0.000673134	0.0026439
LED Off, MCU Running	0.047	3.3	0.644	100	0.1551	0.0644	0.00998844	0.039232064
LED On,MCU sleeping	2.18	3.3	10	2	7.194	0.02	0.14388	0.565124215
LED Off, MCU Sleeping	0.033	3.3	459.4	2	0.1089	0.9188	0.10005732	0.392999822
					Total average power		0.254598894	

We can observe from the energy model that the contribution made by LED off, MCU running state has reduced considerably and the total average power has reduced to 0.254mW. Using this clock steup has reduced the power consumption while waking up from the sleep mode. The following change was made to the code:

```
#define CLOCK_SETUP 0

#ifdef CLOCK_SETUP
#if (CLOCK_SETUP == 0)
  #define DEFAULT_SYSTEM_CLOCK         20971520u           /* Default System clock value */
  #define MCG_MODE                     MCG_MODE_FEI /* Clock generator mode */
  /* MCG_C1: CLKS=0,FRDIV=0,IREFS=1,IRCLKEN=1,IREFSTEN=0 */
  #define SYSTEM_MCG_C1_VALUE          0x06U               /* MCG_C1 */
  /* MCG_C2: LOCRE0=0,RANGE0=2,HGO0=0,EREFS0=1,LP=0,IRCS=0 */
  #define SYSTEM_MCG_C2_VALUE          0x24U               /* MCG_C2 */
  /* MCG_C4: DMX32=0,DRST_DRS=0,FCTRIM=0,SCFTRIM=0 */
  #define SYSTEM_MCG_C4_VALUE          0x00U               /* MCG_C4 */
  /* MCG_SC: ATME=0,ATMS=0,ATMF=0,FLTPRSRV=0,FCRDIV=0,LOCS0=0 */
  #define SYSTEM_MCG_SC_VALUE          0x00U               /* MCG_SC */
/* MCG_C5: PLLCLKEN0=0,PLLSTEN0=0,PRDIV0=0 */
  #define SYSTEM_MCG_C5_VALUE          0x00U               /* MCG_C5 */
/* MCG_C6: LOLIE0=0,PLLS=0,CME0=0,VDIV0=0 */
  #define SYSTEM_MCG_C6_VALUE          0x00U               /* MCG_C6 */
/* OSC0_CR: ERCLKEN=1,EREFSTEN=0,SC2P=0,SC4P=0,SC8P=0,SC16P=0 */
  #define SYSTEM_OSC0_CR_VALUE         0x80U               /* OSC0_CR */
/* SMC_PMCTRL: RUNM=0,STOPA=0,STOPM=0 */
  #define SYSTEM_SMC_PMCTRL_VALUE      0x00U               /* SMC_PMCTRL */
/* SIM_CLKDIV1: OUTDIV1=0,OUTDIV4=0 */
  #define SYSTEM_SIM_CLKDIV1_VALUE     0x00U               /* SIM_CLKDIV1 */
/* SIM_SOPT1: USBREGEN=0,USBSSTBY=0,USBVSTBY=0,OSC32KSEL=3 */
  #define SYSTEM_SIM_SOPT1_VALUE       0x000C0000U         /* SIM_SOPT1 */
```

The following screenshot was taken with AD 2 for this optimization:



LESSONS LEARNED

- Learned to optimize a given system for power consumption using an energy model.
- The impact of different MCU configurations on system power consumption was studied in this project.
- Changes that can be applied to the circuit on FRDM-KL25Z board so as to decrease overall power consumption was studied.

CONCLUSION

The given system was optimized for power consumption using energy model and the impact of each optimization attempt on the system power consumption was studied in the process. Final total average power of **254 µW** was obtained. The power consumption was decreased by a factor of **18.11**.