Clean Energy is a Dirty Business

The Use of Recovered Abrasive Slurry for Silicon Ingot Slicing in the Photovoltaic Industry: Quality, Cost, Environmental Sustainability

"There is always something," said Sonrick Enriquez Soler (Sonny), the Chief Technology Officer at Bituin Marikit Corp., as he listened to the report of the R&D manager, Ricardo Enyero Delgado (Red). For weeks now, they had been trying to qualify the use of recovered polyethylene glycol (PEG) and silicon carbide (SiC) used in ingot slicing, When they solved one problem, another one cropped up, like a multi-headed *hydra* or the mythological *kraken* that could not be contained.

"This is a tough business we got ourselves into," Sonny continued. "Competitors -- particularly the Chinese -- doing all they can to dominate the market."

The silicon ingot wafering operation was indeed a very challenging process. From the moisture content, metals concentration, to the coolant color – and from the circularity values to the amount of silicon kerf loss in the abrasive slurry (percentage fines) -- the technical problems seemed insurmountable given the resources available to the company. Furthermore, time was running out because the company board had given notice that they would pull the plug if the cost of operations could not be reduced to profitable levels in the next six months.

"What is your recommendation?" Sonny asked Red.

Red answered: "We need to set up a pilot scale line that will simulate the entire process, so that we can investigate all the technical issues before trying it out at the production level. This will only cost about

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₱30 million to ₱ 50 million [USD 603,396 - 1,005,718][i] to set-up. We are in frontier territory -- if we want to compete, we have to put this up or else close shop."

"That is a lot of money," said Sonny.

"It's a drop in the bucket compared to what we lost and what we are going to lose. We have to do it," Red retorted.

Sonny whispered under his breath, "Maybe."[1]

Solar Energy and the Solar Wafering Process

Throughout its history and development, solar energy has been trumpeted as a clean source of energy, a renewable energy resource. What is not generally known is that the production of solar wafers depends on the intensive use of an oil-based material and ancillary sub-processes that require high energy inputs, for example the production of the SiC abrasives.

A company like Bituin Marikit Corp. (BMC), with a peak capacity of 800,000 to 1 million wafers per week, could go through 10,000 tons of abrasive slurry material per month.[2] A material of this quantity had to be disposed of one way or the other. The obvious and most readily implementable solution was landfilling, but that solution was unsustainable in the long run.

To mitigate this eventuality, a recycling process had to be implemented to reuse the material for several more cycles before sending it to the landfill. Alternatively, the company could find a viable application for the spent material in another company or industry. Either of these initiatives would also help BMC remain competitive by reducing manufacturing cost. Competitive pressures, particularly from manufacturers in China, necessitated the use of recovered material, otherwise BMC's product cost would become too high compared to the competition.

These difficult circumstances mandated that Sonny, as CTO, lead the company's continuous improvement program on silicon photovoltaic wafer manufacturing in terms of process optimization, materials substitution for cost improvement, new technology development, and materials recycling.[3]

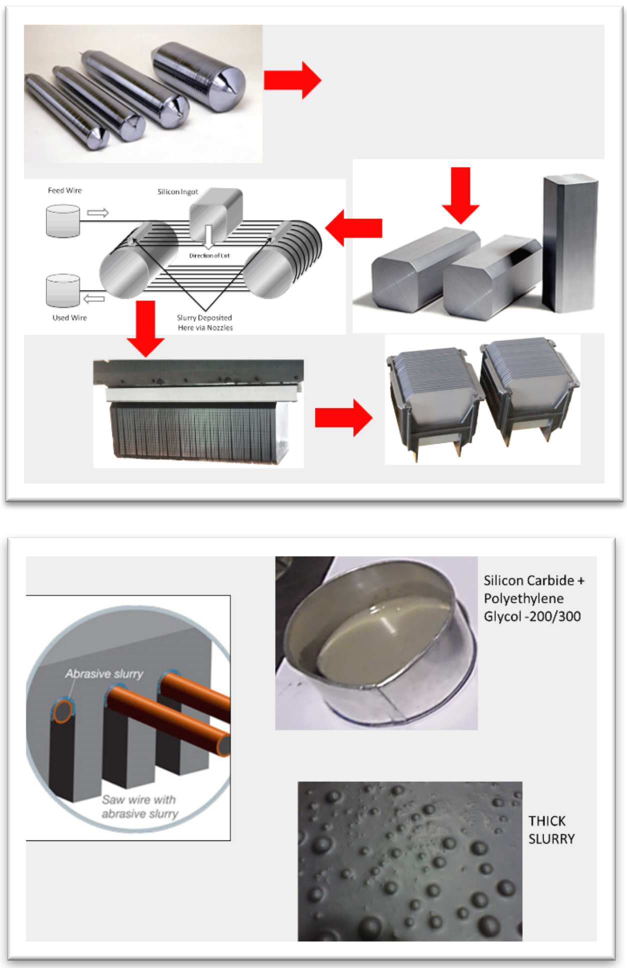
Production of Solar Wafers

With the increasing installation capacity of solar photovoltaic panels, manufacturing operations to produce the solar wafers were also increasing, with the concomitant increase in the use of raw materials. One of the direct materials in the production of solar wafers was the *slicing slurry*, which was a suspension consisting of abrasive grits (particles) and a liquid coolant with 1:1 ratio by mass. The abrasive particles used were silicon carbide (SiC) and the coolant used was polyethylene glycol (PEG 200/300). For sustainability, and to ease the introduction of this material into the environment once it was spent, the abrasive particles and the coolant had to be recycled and re-used, because this would drive down the cost of slicing silicon ingots into solar wafers. Slurry suspension homogeneity was a critical factor to obtain the optimum cutting capacity. Large variations in the particle diameter presented an impediment to achieving this goal of a homogenous mixture. This was due to a higher probability of particle separation, which arises from different responses of particles with different sizes to fluid motion and colloidal forces. Increasing

i Forex conversion of 1 USD =49.7450PHP on December 12, 2016, http://www.xe.com/currencyconverter/convert/?Amount=50%2C000%2C000&From=PHP&To=USD

the concentration of fine particles in the slurry increases the probability of thick slurry formation in the suspension.[4] This tendency to increase viscosity as more fine particles are introduced can be linked to the formation of silanol compounds onto the surface of the silicon fine particles.[5] These chemical groups combine with each other to form networks of silicon particles, thereby promoting the thickening of the slurry.

Figure 1
Silicon ingot wafer slicing process



Source: Public Domain Images

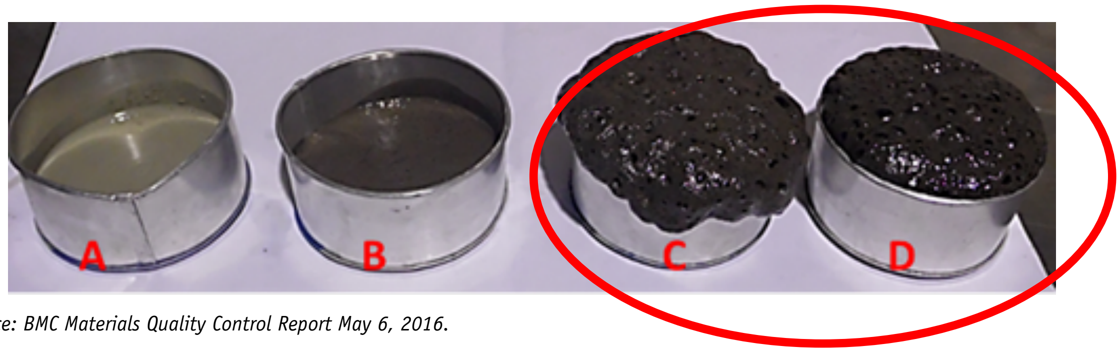
Background on BMC, a Solar Wafering Company

BMC was established in 2012 with an initial capitalization of $13,000,000.[6] Its maximum capacity was reached in 2014 producing 1,000,000 wafers per week using 60 silicon ingot wireslicing machines. BMC immediately captured a large percentage of the market supplying wafers to five customers, such as Fusionstar and Spectra Energy. One of its strategies was to reuse the SiC/PEG abrasive slurry a number of times to reduce the wafering cost. Around the middle of 2015, engineers started reporting quality issues of roughness values above specifications and of surface stains that were eventually traced to the quality of the abrasive slurry.[7]

The Wafering Process

In the conversion of SiO_2 (quartz) into silicon photovoltaic cells, part of the value chain of processes is called *wafering*. In this process, a continuous strand of stainless steel wire about 120 microns in diameter is wound around two parallel guide rollers, forming a bed of about 2,500 – 3,000 loops from the line of wire. A silicon ingot of around 800 mm in length is slowly pressed down on this bed of wire, transforming it into 2,500 to 3,000 slices or "wafers" of about 150 microns to 200 microns in thickness. The machine used for this process is called a *wiresaw machine*. The slicing of the ingot into thousands of wafers is done simultaneously over a period of about six to eight hours depending on the size of the ingot.[8]

Figure 2
Thickening of abrasive slurry due to excessive amount of percentage fines

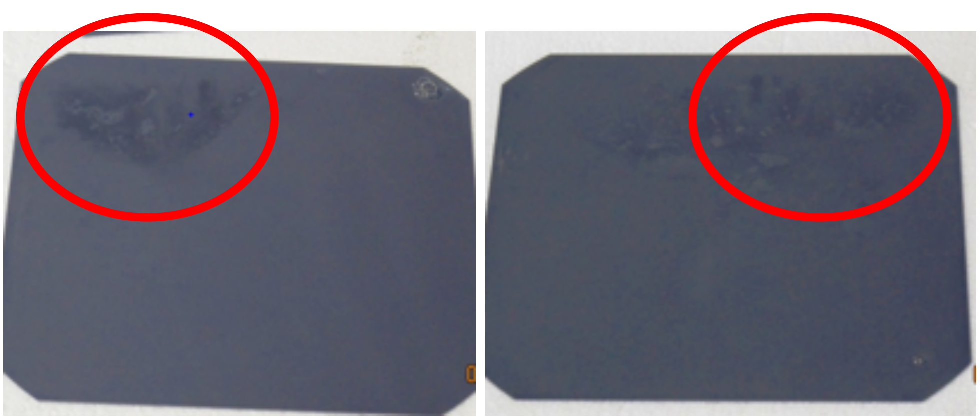


Source: BMC Materials Quality Control Report May 6, 2016.

Thick Slurry/Cosmetic Defects

The wiresawing process has two types: 1) the fixed abrasive machining wherein the wire is coated with diamond grits and does the actual cutting, and 2) the free abrasive machining wherein the wire only acts as a carrier of the cutting slurry medium. This slurry consists of a suspension of micron-sized silicon carbide abrasive particles (SiC) in a liquid coolant. The liquid coolant commonly used is polyethylene glycol 200-300 (PEG). The stability of the suspension of this slurry directly affects the efficiency and quality of the ingot slicing. Thickening of the slurry during the cutting process results in defects such as surface stains called *cosmetic defects* that lower the productivity yield of the manufacturing operation.[9]

Figure 3
Cosmetic stains/defects due to thick slurry cutting



Source: BMC Materials Quality Control Report May 6, 2016.

BMC'S Weekly Meeeting

"Good morning," Sonny started the weekly meeting of the staff and engineers. "Let's start with marketing. What do we have, Hyren?

"Hello everyone," Hyacinth Renwin Reyes, the marketing manager, greeted the team. "I just got back and came straight here from the airport. I took the red-eye from Spectra Energy's headquarters in Baden-Baden, Germany. From the latest round of negotiations with our customers, this will be our average consolidated volume and selling price for the week." She showed the Table 1.

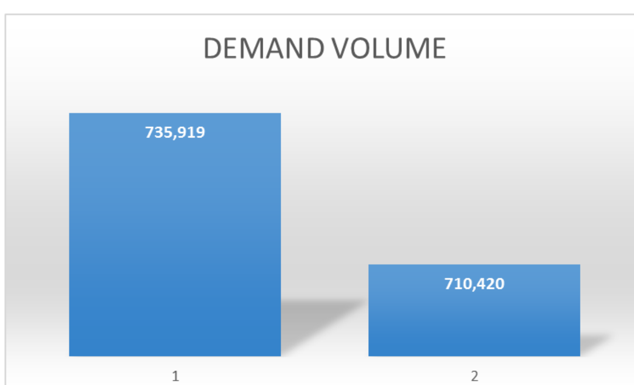
Table 1
Selling price per wafer (SPW) marketing schedule

			SELLING PRICE PER WAFER $	**0.930**	**0.850**	**0.730**	**0.664**	**0.662**
			VOLUME	**625,185**	**683,385**	**748,627**	**797,536**	**812,374**
SLURRY	**YIELD %**	**VOLUME**						
A	97	788,453		706,819	735,919	768,540	792,995	800,414
B	95	672,213		648,699	677,799	**710,420**	734,875	742,294
			$(VOL_{SPW} + VOL_{YIELD}) \div 2$					
C	93	609,110		617,148	646,248	678,869	703,323	710,742
D	90	537,423		581,304	610,404	643,025	667,480	674,899
E	87	511,708		568,447	597,547	630,168	654,622	662,041

Source: BMC Marketing Department Report. June 30, 2016

"Customers' confidence is slightly eroding as we did not meet our yield commitment last week," Hyren continued, "that is why our volume is on the downward trend. I had to lower our selling price per wafer (SPW) to show our commitment to improving our processes and also to keep us in the game. Otherwise, we would lose everything." She showed the Figure 4.

Figure 4
Wafer market demand volume trend



Source: BMC Marketing Department Report. June 30, 2016

Sonny turned to the finance manager, Evette Oliveros, asking "What is our financial performance to date Vet-Vet?"

Vet-Vet presented Table 2.

Table 2
BMC weekly financial performance

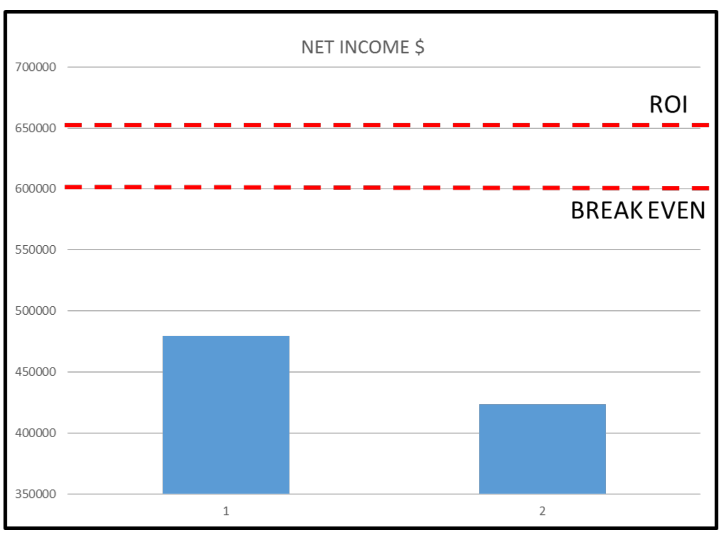
D = 768,540 WAFERS SPW = $ 0.730

SLURRY	CPD	YIELD	VOLUME OUTPUT	GROSS INCOME	SILICON LOSS	NET INCOME
	$	%	YIELD x D	SPW x VOLUME OUPUT	(D - VOLUME OUTPUT) x SPW	(GROSS INCOME) - (SILICON LOSS) - CPD
				$	$	$
A	172,472.73	97	745,484	544,203	16,831.03	354,899.42
B	91,561.56	95	730,113	532,982	28,051.71	413,369.22
C	**58,743.52**	**93**	**714,742**	**521,762**	**39,272.39**	**423,745.89**
D	51,086.30	90	691,686	504,931	56,103.42	397,741.06
E	26,864.42	87	668,630	488,100	72,934.45	388,300.89

Source: BMC Finance Department Report. June 30, 2016

"This is our net income for last week: slurry usage is 0.099 liters per wafer," she said. "Our net income again did not meet breakeven, much less meet our ROI commitment." (See Figure 5)

Figure 5
BMC ROI target performance



Source: BMC Finance Department Report. June 30, 2016

Sonny looked at the materials engineering manager, Eidelweis "Eedie" Castel, a tall (5'8") Filipino-Italian, for answers. Eedie responded with her report: "Our engineering runs still indicate yield performance for the following type of slurries." (See Table 3)

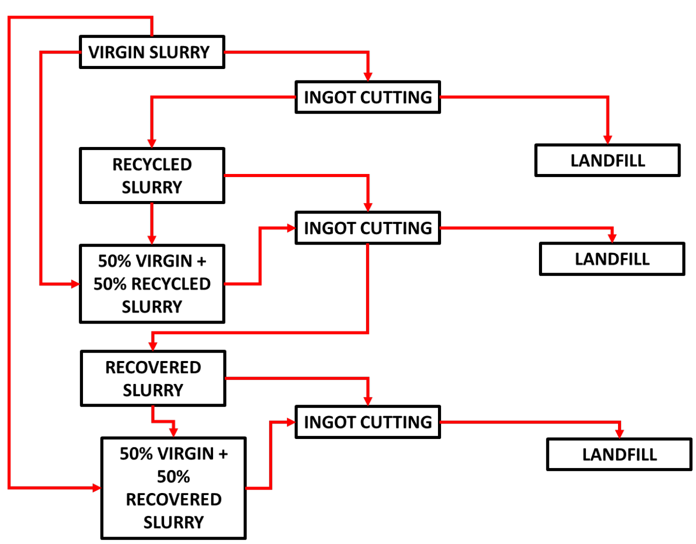
Table 3
Wafer cost per demand volume (CPD) calculator [19].

				COST PER DEMAND VOLUME (CPD), CPW x D				
			VOLUME	768,540	710,420	678,869	643,025	630,168
	SLURRY	YIELD	CPW					
		%	$	$	$	$	$	$
A	VIRGIN	97	0.215590909	165,690.24	153,160.09	146,357.98	138,630.34	135,858.49
B	VIRGIN + RECYCLED	95	0.114451948	87,960.90	81,308.95	77,697.88	73,595.46	72,123.96
C	RECYCLED	93	0.073429403	56,433.43	52,165.72	49,848.95	47,216.94	46,272.86
D	VIRGIN + RECOVERED	90	0.063857873	49,077.33	45,365.91	43,351.13	41,062.21	40,241.19
E	RECOVERED	87	0.033580519	25,807.97	23,856.27	22,796.77	21,593.11	21,161.37

Source: BMC Materials Engineering Department Report. June 30, 2016

"Since we are implementing the following scheme for slurry usage," Eedie said as she presented Figure 6, "about 2% of the cuts were "infected" by the thick slurry issue that resulted in an overall yield of 90% well below our target of 95%."

Figure 6
Abrasive slurry usage and recycling plan [20].



Source: BMC Materials Engineering Department Report. June 30, 2016

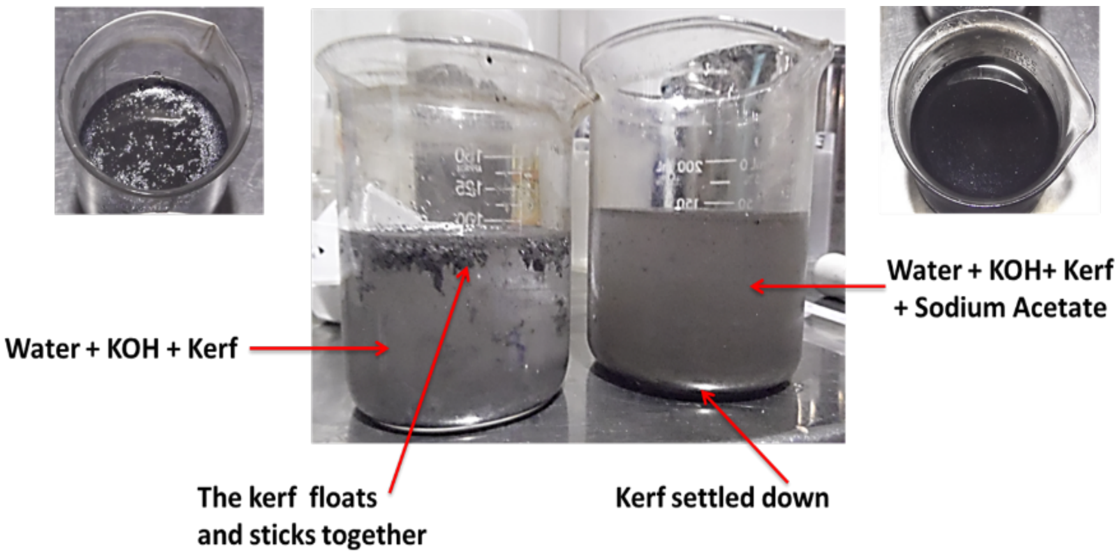
"Ok, Red, what is the news from the frontier?" Sonny directed everyone's attention to the R&D manager.

Red replied, "Well, first off, corporate planning has just released their report indicating that the ROI for R&D projects is 7.5 times R&D total expenses. That being said, the following are the investigations and projects we are currently pursuing:"

A. Thick Slurry Investigation

Figure 7

Silicon kerf behavior in KOH solution and in KOH + Sodium Acetate solution [21].



Source: BMC R&D Department Report. June 30, 2016.

Red continued presenting Figure 7, "From our investigations, we have determined that the silicon kerf in the solution with sodium acetate settled out of the suspension and deposited to the bottom of the beaker. In contrast, the kerf in the solution with potassium hydroxide (KOH) only remained in suspension and formed aggregates of silicon particles. It is presumed that the acetate ion bonded with the very reactive silicon particles which caused their sedimenting out of the suspension. Adding sodium acetate to the slurry could be one way to prevent thick slurry formation."

B. Waste Recovery – Filtration: In-House vs. Third Party (SCM)

"Looks promising,",said Sonny, "What else do you have"?

"Well, we have successfully developed an in-house process to recover the waste PEG and SiC. This is the cost analysis of the process against the current third party supplier,"Red reported.

Cost Analysis:[10]

1. Cost of electricity = ₱8.248/KwH
2. Conversion rate = ₱43.76 to $1.00
3. Filter press operation
    A. Recovery rate = 77%
    B. Output rate using 30 plates = 3,000 liters/week
    C. Hydraulic motor rating = 3 Kw
    D. No. of hours of operation = 168 hrs. /week
    E. Energy requirement per week = C x D = 504 KwH
    F. Cost to operate per liter recovered = (₱8.248 x E) /3,000 liters = ₱ 1.38/ L
    G. Cost of filter cloth = ₱1,980/pc.
    H. Output per pc. of filter cloth = 100 liters/week

   I. Filter cloth end of life = 50 weeks (1 year)
   J. Total output per pc. of filter cloth before replacement = 5,000 liters
   K. Cost of filter cloth per liter recovered = G/J = ₱0.396/liter
   L. Total cost of filter press operation per liter recovered = F + K = ₱1.78/liter
4. Air pump operation
   A. Cost of air pump operation = 5.36 CFM per Kw
   B. Pump flowrate = 31 CFM
   C. No. of hours of operation = 168 hours/week
   D. Energy requirement per week = (N / M) x O = 972 KwH
   E. Cost to operate per liter recovered = (₱8.248 x P) /3,000 liters = ₱ 2.67/liter
5. PEG drying operation
   A. Energy required to dry per liter recovered = 0.157 KwH/liter
   B. Cost to dry per liter recovered = ₱ 8.248 x R = ₱ 1.29/liter
6. Labor Cost
   A. No. of operators = 3
   B. Cost of labor per week = ₱ 6,600/week
   C. Labor cost per liter recovered = ₱ 2.20/liter
7. Total cost of operation per liter recovered = L+Q+S+V = ₱ 7.94/liter
8. Total cost per Kg recovered (density = 1.09) = $ 0.16/Kg ($0.18/liter

Potential Savings vs. SCM = $ 0.44/Kg (SCM) - $0.16/Kg = $0.28/Kg

"Other projects in the works are the sludge (waste abrasive slurry) to concrete hollow blocks and the polyurethane-sludge composite material." Red ended his report showing the pictures of the prototype materials in Figures 8 and 9.

C. Sludge to Concrete Hollow Blocks – CHB

Figure 8
Concrete hollow block prototype with waste abrasive slurry filler

Source: BMC R&D Department Report. June 30, 2016.

D. Polyurethane Filler

Figure 9
Polyurethane matrix composite with waste abrasive slurry reinforcing filler

Source: BMC R&D Department Report. June 30, 2016.

There was a momentary pause as the team has started to see the "writing on the wall." The tension in the air was so palpable that it could almost be cut with a knife.

Sonny, the consummate leader that he was, kept the spirit on the upbeat. "Alright, Eedie, please work closely with Red to solve the thick slurry issue. Red, please prepare your proposal for presentation in the next Board meeting. Good work everybody. If we hit 95% overall yield, the ice-cream is on me."

Endnotes

[1] Interview with Sonrick E. Soler, Chief Technology Officer at Bituin Marikit Corp, on June 9, 2016, and Interview with Ricardo E. Delgado, R&D manager at Bituin Marikit Corp, on June 9, 2016.
2 Interview with Ricardo E. Delgado, R&D manager at Bituin Marikit Corp, on June 9, 2016.
3 Interview with Sonrick E. Soler, Chief Technology Officer at Bituin Marikit Corp, on June 9, 2016.
4 Interview with Ricardo E. Delgado, R&D manager at Bituin Marikit Corp, on June 9, 2016.
5 Ibid.
6 BMC Articles of Incorporation, 2012.
7 Interview with Eidelweis M. Castel, materials engineering manager at Bituin Marikit Corp., on June 10, 2016.
8 Meyer Burger, “Wafer Production” http://www.meyerburger.ch/en/company/about-meyer-burger/wafer-production/ and www.meyerburger.ch Accessed December 13, 2016
9 BMC, Materials Quality Control Report. May 6, 2016.
10 BMC, R&D Department Report. June 30, 2016.