WAFER WIRE SAWING ECONOMICS AND TOTAL COST OF OWNERSHIP OPTIMIZATION

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BACKGROUND

Wafer slicing, also called “wafering,” is a key part of the solar photovoltaic (PV) cell manufacturing process. The process begins with solid ingots of single-crystal or multi-crystalline silicon material. Wire saws shape the ingots into squared blocks and then slice them into thin wafers. These wafers are used as the base for the active PV cell. With wafer cost responsible for over 50% of c-Si total solar module cost, reducing wafer manufacturing costs is critical to the goal of making solar energy competitive with grid power. This paper analyzes the various wafer cost drivers, in particular the impact of the wafer sawing process step; compares the various cost reduction options available to wafer manufacturer; and demonstrates the powerful effect of higher load size in driving down cost.

INDUSTRY CHALLENGES

The rapid explosion of solar energy is fueled by a reduction in cost/watt. Because silicon and wafering represent over 50% of total cost (Fig.1), advances in wafering technology are critical to achieve industry cost objectives. The near term industry target of < $1/Watt module manufacturing cost cannot be achieved without a clear strategy to reduce wafer cost.

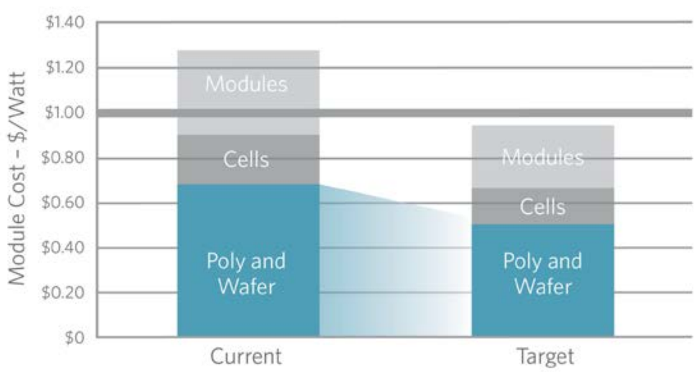


Figure 1: Wafer cost contribution to module cost and industry challenge

The total wafer cost depends on five components: the material yield, or number of wafers produced per kilogram of silicon ingot; the cost of the silicon itself; the quality yield, or number of wafers which meet specifications; and the consumables and capital cost of the sawing process. Of these, wafering technology defines the material yield, quality yield, and consumables and capital costs, which together account for 2/3 of the total cost. Wafering also indirectly impacts the silicon cost since sawing thinner wafers cost effectively largely depends on the sawing process optimization.

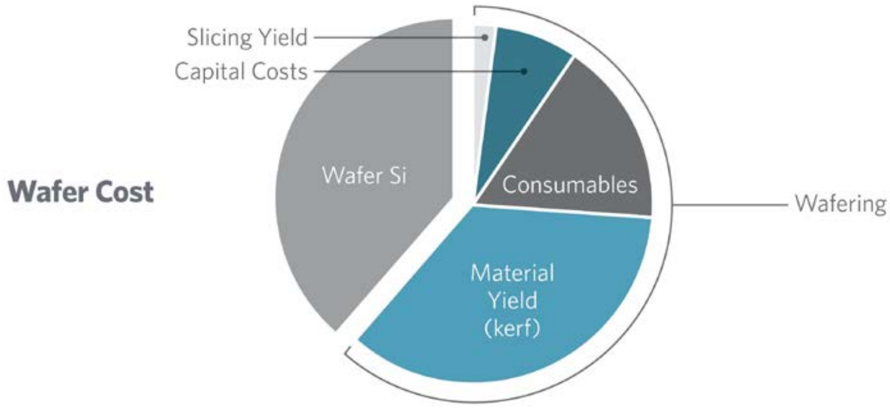


Figure 2: Wafer cost breakdown

To drive down solar PV cost per Watt and meet the near term industry target of <$1/Watt total module manufacturing cost, the industry needs continued optimization of wire sawing processes and technologies.

WAFER WIRE SAWING ECONOMICS

Let us take a closer look on how wafer and wafer wire sawing economics work. The following formula shows the wafer Total Cost of Ownership (TCO) processed by a wire saw:

$$\frac{Total\ cost}{Wafer} = \frac{(Silicon\ cost\ per\ cut + Consumables\ cost\ per\ cut + Fixed\ cost\ per\ cut)}{Total\ number\ of\ yielded\ wafers\ per\ cut}$$

Figure 3: Wafer TCO formula

Where

$$Total\ number\ of\ yielded\ wafers\ per\ cut$$
$$= Quality\ Yield * Material\ Yield * Theoretical\ number\ of\ wafers\ per\ cut$$

$$Quality\ yield = \frac{\#\ of\ wafers\ within\ specifications\ per\ cut}{\#\ of\ wafers\ produced\ per\ cut}$$

$$Material\ Yield = 1 - kerf\ loss\ and\ \ Kerf\ loss = \frac{(wire{+}slurry\ SiC)thickness}{(wire{+}slurry\ SiC)thickness{+}wafer\ thickness}$$

$$Theoretical\ number\ of\ wafers\ per\ cut = \frac{Length\ of\ silicon\ bricks\ loaded\ per\ cut}{Wafer\ thickness}$$

Quality and material yield are two fundamental drivers of wafer TCO, as shown in the mathematical formula. Wafer manufacturers look for a minimum of 95% quality yield with increasingly tight wafer specifications. Material yield, typically 50-55%, is the largest loss term in the equation and is fundamentally driven by wire diameter-related kerf loss.

"Silicon cost per cut" is the cost of the silicon bricks loaded into the wire saw per cut. This cost includes the raw silicon cost necessary to make the bricks in addition to the conversion cost from raw silicon to bricks. This conversion cost includes the crystallization, squaring, cropping and grinding and chamfering process steps. We define it here as:

$$Silicon\ cost\ per\ cut = \ raw\ silicon\ cost\ per\ cut\ + brick\ conversion\ factor$$

With

$$Raw\ silicon\ cost\ per\ cut = \ weight\ of\ the\ bricks\ per\ cut * raw\ silicon\ price\ per\ kg$$

The "Consumable cost per cut" is the sum of wire, slurry and all the other consumables costs such as glue, beam, pulleys and wire guide coating and grooving, per cut. This term is largely driven by wire and slurry with equal weight for each:

$$Consumables\ cost\ per\ cut\ = \sum (Slurry + wire + others) per\ cut$$

Where

$$Wire\ cost\ per\ cut = wire\ speed * time\ to\ execute\ the\ cut * wire\ price$$

and

$$Time\ to\ execute\ the\ cut = \frac{total\ area\ to\ cut}{Productivity}$$

and

$$Productivity = \frac{table\ speed * brick\ load\ size * wafer\ length}{wafer\ thickness + kerf\ loss}$$

*W*here

$$Slurry\ cost\ per\ cut = slurry\ volume\ per\ unit\ area * total\ area\ to\ cut * slurry\ price$$

and

$$Total\ area\ to\ cut = \frac{brick\ load\ length * wafer\ surface\ area}{wafer\ tickness + kerf\ loss}$$

The "Fixed cost per cut" is the sum of the yearly tool depreciation, facilities (power, water, air consumptions) and factory floor space related costs divided by the number of cuts per year:

$$Fixed\ cost\ per\ cut\ = \frac{(\sum Tool\ depreciation + facilities\ consumption + floor\ costs) per\ year}{\#\ of\ cuts\ per\ year}$$

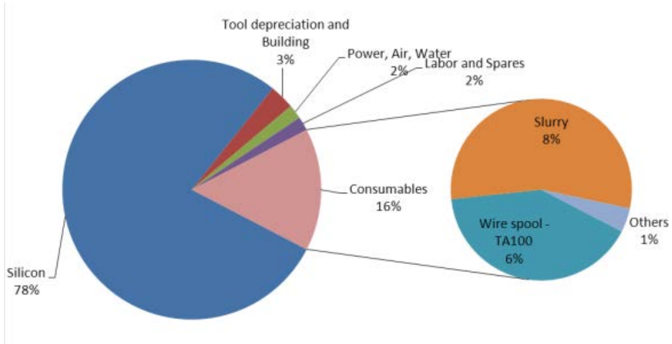


Figure 4: Typical Yielded Wafer TCO Breakdown Post Wire Sawing
(Application: 120µm wire, 180 µm wafer, 1700 mm load)

WAFERING COST DRIVING FACTORS AND SENSITIVITY ANALYSIS

Having identified the components of wafer TCO, we are now ready to analyze the key parameters driving the various terms of the wafer TCO equation and the complex relationships between them. The table presents these key parameters along with their positive impacts and trade-offs:

Cost driving factors	Wafer TCO terms positively impacted	Wafer TCO trade-offs
Raw silicon market price	Silicon cost per cut	None
Wafer thickness	Theoretical numbers of wafers per cut	Consumables cost per cut, Fixed costs per cut, Quality yield
Wire thickness	Material yield	Quality yield, consumables cost per cut, Fixed costs per cut
Table speed	Fixed cost per cut, Consumables cost per cut (wire)	Quality yield
Slurry recycling	Consumables cost per cut	Quality yield
Wire speed	Consumables cost per cut	Quality yield

Clearly driving down wafer cost is a complex problem involving both market forces and wire sawing process optimizations. Beyond the obvious reduction in price of raw silicon, all other cost reduction drivers come with trade-offs attached to them. Let us now look at some of the sensitivities:

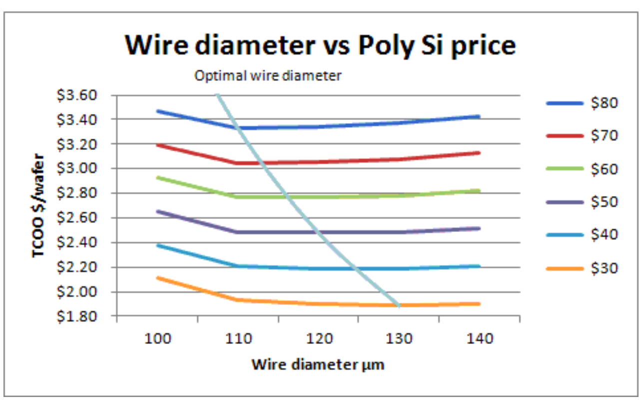
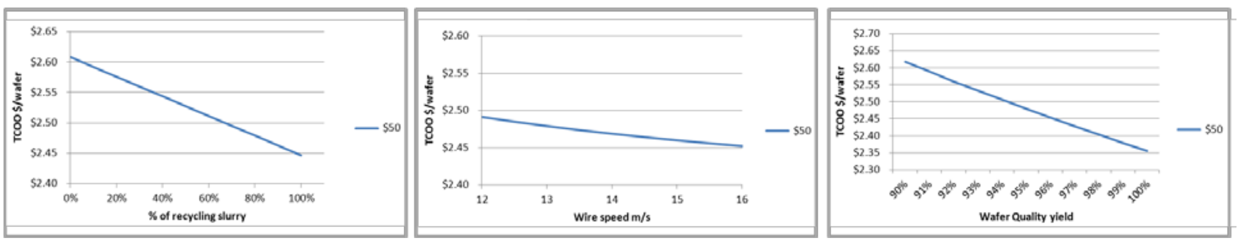


Figure 5: Optimal Wire Diameter vs Raw Silicon Market Price

Fig.5 shows the trade-off effects of thinner wire for various raw silicon market prices. As shown here, the optimal wire size to use depends on raw silicon pricing. As raw silicon cost moves down, so does the value of material yield improvement relative to the trade-offs of higher consumables cost per cut (higher wire price, lower productivity) and higher fixed cost per cut (lower productivity). If we were to add in the expected quality yield challenges, the trade-off effects would be even more pronounced. Wire saw makers need to ensure their tools are thin wire-compatible, but may not want to use the thinnest available wire when silicon costs are low.

As expected, slurry recycling % has a major effect on wafer TCO if we assume that the quality yield is kept under control (Fig. 6). The industry is rapidly moving to 80% slurry recycling. Fig. 7 shows the small effect of wire speed on wafer TCO. As wire speed decreases, so does table speed in order to maintain quality yield. Net effect on wafer TCO is unfortunately not very significant. Fig.8 illustrates the powerful effect of even a single yield point on TCO. Clearly maximizing yield is paramount. Whatever process optimizations can be achieved on the sawing tool cannot be at the expense of wafer quality yield.

Given the trade-offs inherent in wafer TCO, what can wire saw makers and process developers do to help drive wafer cost down while significantly improving the manufacturer’s bottom line?



Figures 6 - 8: Slurry Recycling Rate, Wire Speed and Quality Yield vs Cost per Wafer

THE ECONOMIC EFFECT OF HIGHER BRICK LOAD SIZES

LOAD, TABLE SPEED, YIELD AND PRODUCTIVITY

Brick load size is a very special parameter. As we have seen, brick load length shares a special relationship with table speed and productivity:

At constant productivity, wafer and wire thickness, load and table speed have a 1/x relationship. As load increases, table speed can decrease even faster while keeping productivity unchanged. This means that as load increases, we can lower table speed enough to maintain maximum quality yield, yet still keep table speed high enough to increase productivity. In addition, as load increases, tool availability increases because the frequency of load swaps decreases. This, in turn, further boosts productivity.

Let us see how this works for 120µm wire size, 180µm wafer size, a real case tested at Applied HCT R&D facilities (Figure 9). Starting with a baseline load of 0.85m and table speed of 380µm/min for best in class yield of 98.6%, load is gradually increased to 1.1 and 1.73m. Table speed is decreased to maintain the highest yield but productivity is increased from 7.4 MW/Y to 9.2 MW/Y, a 20% jump in output with no compromise on quality yield.

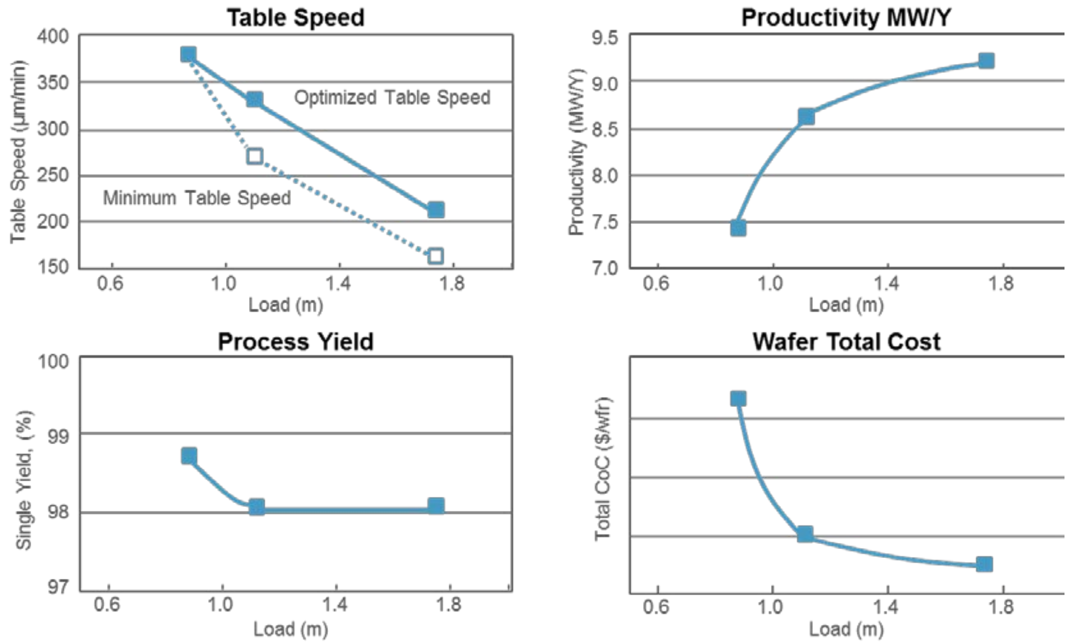


Figure 9: Table Speed, Productivity, Process Yield and Total Wafer Cost

Fig. 10 illustrates the improvement in tool availability with increasing load size. As load increases, less frequent load swaps need to occur, freeing the tool up to cut more often.

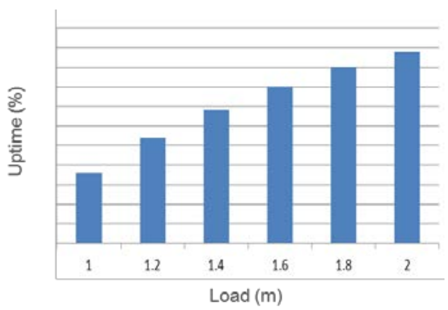


Fig. 10: Availability Advantage

NO COMPROMISE ON QUALITY YIELD

Fig. 11, 12 and 13 provide the metrology charts for the 0.85m and 1.73m loads, demonstrating that load increase can deliver productivity without compromising quality yield. Yield of 98% at 30µm TTV, 20µm TV and 20µm saw mark is achieved using 1.73m load and 210µm/min table speed.

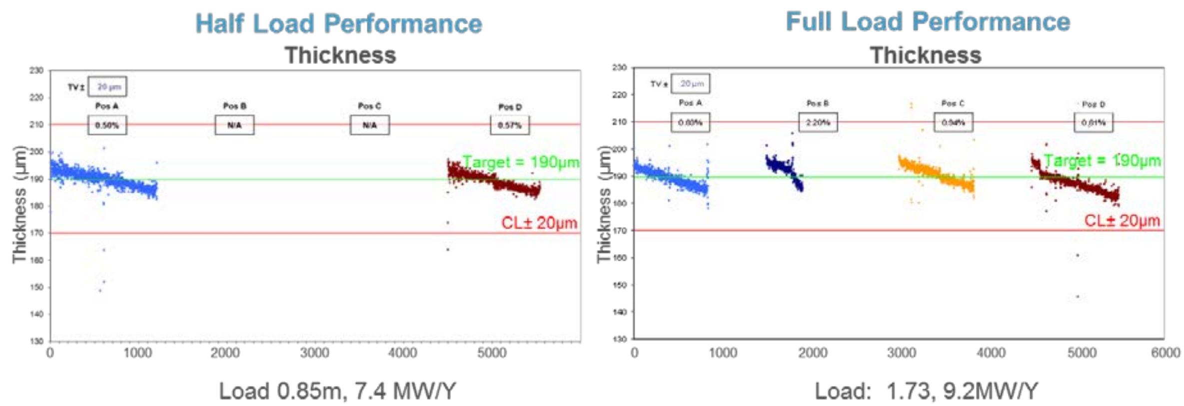


Figure 11: TV Comparison Chart

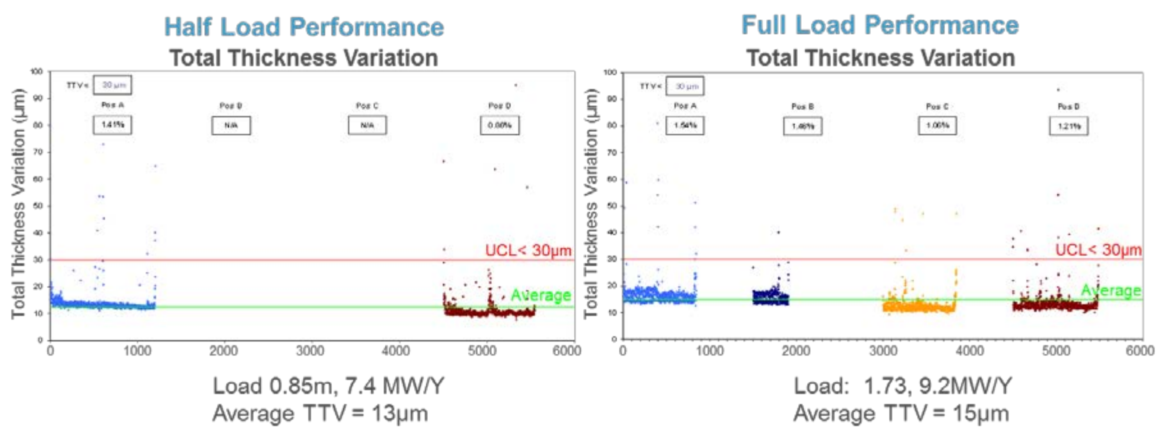


Figure 12: TTV Comparsion Chart

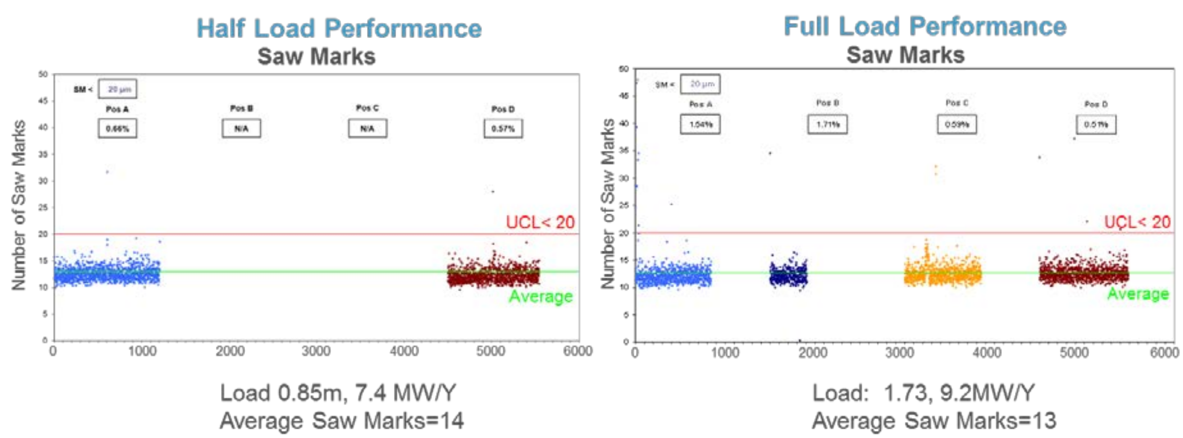


Figure 13 : Saw Marks Comparison

NET ECONOMIC BENEFITS FOR WAFER MAKERS: LOWER WAFER TCO AND INCREASED NET CASH FLOWS PER TOOL

Increased productivity without compromise on quality yield has a net effect on wafer TCO. Between 0.85m load and 1.73m load, the 20% productivity advantage yields a 5¢/wafer TCO advantage. At 0.95m load, the TCO advantage exceeds 3¢/wafer.

Beyond TCO, higher load sizes offer another economic benefit for wafer makers: higher net cash flow generation per tool per year. Fig. 14 illustrates the net cash flows generated by a 0.95m load tool and by a 1.73m load tool for a 5 year project. Wafer selling price is taken to be $3/wafer in both cases for comparison purposes.

	Year1	Year2	Year3	Year4	Year5	
9.3MW/Y @ $3/wafer	$ 7,3	$ 7,3	$ 7,3	$ 7,3	$ 7,3	
9.3MW/Y @$2.17/wafer	$ 5,3	$ 5,3	$ 5,3	$ 5,3	$ 5,3	
Net cash flow	$ 2,0	$ 2,0	$ 2,0	$ 2,0	$ 2,0	**$ 10,2**
Discounted net cash flow (NPV)	$ 1,9	$ 1,7	$ 1,5	$ 1,4	$ 1,3	**$ 7,7**

Assumptions : 120µm wire, 180µm wafer thickness, 210µm/min table speed, optimal 1.73m load at 98%

	Year1	Year2	Year3	Year4	Year5	
7.9MW/Y @ $3/wafer	$ 6,3	$ 6,3	$ 6,3	$ 6,3	$ 6,3	
7.9MW/Y @$2.20/wafer	$ 4,6	$ 4,6	$ 4,6	$ 4,6	$ 4,6	
Net cash flow	$ 1,7	$ 1,7	$ 1,7	$ 1,7	$ 1,7	**$ 8,4**
Discounted net cash flow (NPV)	$ 1,5	$ 1,4	$ 1,3	$ 1,1	$ 1,0	**$ 6,4**

Assumptions : 120µm wire, 180µm wafer thickness, 360µm/min table speed, 0.95m load at 98.5%

Figure 14: Comparison of Cash Flows Generated Over 5 Years

After discount at 10% discount rate, the 1.73m load tool offers a $7.7M cash flow NPV versus a $6.4M for the 0.95m tool. This is a 20% advantage or $1.3M NPV difference in total cash flow NPV generated over 5 years between the two configurations.

CONCLUSION

While the key parameters to drive wafer cost down are often counter-balanced by significant trade-offs, wire saw load size flexibility has the unique advantage of enabling higher productivity without compromising quality yield. Specifically, we have seen that in the case of 120um wire size and 180um wafer size, the optimal load size is around 1.7m. At this optimal load size, wafer makers can enjoy a productivity advantage in excess of 20% and 3¢/wafer wafer TCO advantage vs. conventional 1m load tool, which translates into 20% higher cash flow generation over a 5 year project period.

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