

## CONCEPTUAL DESIGN OF PHOTOTHERMAL ELECTROCHEMICAL WATER RESONANT ELECTROLYSIS

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### ABSTRACT

Since there is very limited natural hydrogen source, various methodologies had been proposed to extract hydrogen gas from both renewable and non-renewable resources. Among all, solar fuel or solar hydrogen fuel shows the most fascinating prospect to replace the conventional energy scheme. A detail comparison on both fossil based and solar based hydrogen generation method is reviewed. Although photothermal electrochemical water splitting technique shows highest preliminary efficiency, it is not practical due to cost, material and area requirement. Based on CST dish/Stirling technology, non-hybrid photothermal electrochemical process is approached and compared. By yielding higher hydrogen output without decreasing the water electrolysis efficiency, resonant electrolysis is proposed to integrate with the named solar harvesting technique. Detail discussion is made for the proposed operating system design and the effectiveness of harvest mono-atomic hydrogen fuel through theoretical analysis using both chemical bond and enthalpy of formation technique. The theoretical result shows that the mono-atomic hydrogen contain 3.83 times of energy compare to diatomic hydrogen gas. Last but not least, a conceptual design of resonant electrolysis and working principle is also summarised.

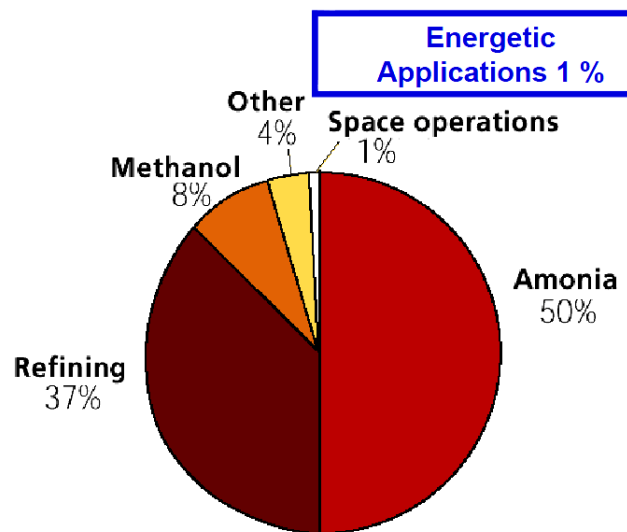
*Keywords:* electrolysis, photothermal electrochemical, resonant, solar energy, concentrating

### INTRODUCTION

Energy is a multifarious entity, which may transform into highly diverse aspects. However, the primary energies that may be directly accessed in nature are limited in number: such as fossil energies such as coal, oil, and natural gas, nuclear energies and renewable energies such as hydro energy, biomass energy, solar energy, wind energy, geothermal energy, and tidal energy. Energy transport is effected by means of an energy carrier. Currently, the two main such carriers are electricity and heat. Tomorrow, however, a new carrier may become dominant – hydrogen. Finally, if energy is to be available at all times, it is essential that there should be the ability to store. Such storage may take a variety of forms. Energy may be stored in mechanical form (potential energy, in the case of the water reservoir of a hydroelectric dam, or kinetic energy, in

the case of a flywheel), or in thermal (hot-water tank), chemical (gasoline tank, primary and storage batteries), or even magnetic (superconducting coil) form.

Although water electrolysis to produce hydrogen (and oxygen) has been known for around 200 years and has the advantage of producing extremely pure hydrogen but it represents only 4% of the world hydrogen production. Refer to Figure 1, hydrogen is used almost entirely for industrial production processes. Utilisation of hydrogen in petroleum refining, ammonia production and metal refining amounts to more than 50 million metric tonnes worldwide in 2006 (Zeng and Zhang, 2010). In general, ninety five percent of produced hydrogen is for in-house consumption, only 5% will be sold on the market (Michal, 2007).



**Figure 1 :** Utilisation of Hydrogen in different industries (Karl et al., 2007)

### **HYDROGEN FUEL PRODUCTION**

As a secondary form of energy, hydrogen is produced by using different energy supply system classes, namely fossil fuels (coal, petroleum, natural gas and as yet largely unused supplied such as shale oil, oil from tar sands, natural gas from geo-pressured location, etc), nuclear reactors including fission reactors and breeders, and renewable energy resources (including hydroelectric power, wind power systems, ocean thermal energy conversion systems including biomass production, photovoltaic energy conversion, solar thermal systems, etc) (Kothari, Buddhi and Sawhney, 2006). The detail of the production methodology is listed in Table 1. Large scale consumptions required large scale of hydrogen production to match them. As such, the hydrogen production is dominated by reforming of natural gas and gasification of coal and petroleum coke, as well as gasification and reforming of heavy oil (Zeng and Zhang, 2010).

Table 1: Hydrogen production process (Federica, Massimo Luca and Valeri, 2010)

Process	Description
Natural gas reforming	Hydrogen is obtained as a product of steam and a hydrocarbon feedstock, usually methane, combined at high pressure and temperature. Carbon dioxide is also produced in the reaction ( $7.33\text{kgCO}_2/\text{kgH}_2$ ) and the energy amount required to operate the reformer is considerably high ( $183.2\text{MJ}/\text{kgH}_2$ ).
Bio-derived liquid reforming	Hydrogen is produced by reforming bio-liquids such as sugars, ethanol, or bio-oils and the process is similar to natural gas reforming; nevertheless, the technology is still under research and needs improvement in the catalyst activity and durability.
Coal gasification	The pulverized coal is oxidized at high temperature with pure oxygen producing a raw gas mixture, which is then desulfurised and processed through a shift reactor to increase the hydrogen fraction. During both the gasification phase and the water-gas-shift process a significant amount of carbon dioxide is produced ( $29.33\text{kgCO}_2/\text{kgH}_2$ ), additionally the coal gasification technology is characterized by a large energy requirement ( $205\text{MJ}/\text{kgH}_2$ ).
Thermochemical hydrogen	The process uses the heat to dissociate water to obtain hydrogen. Alternatively other chemical compounds can be used instead of water, such as sulphuric acid. This technology becomes interesting when renewable power sources are used to obtain the heat for the necessary reactions ( $118.5\text{MJ}/\text{kgH}_2$ ). The thermochemical hydrogen production process is still an immature technology requiring long term development
Water electrolysis	Monopolar alkaline electrolysis units, proton exchange membrane electrolyzers or solid-oxide electrolysis cells are used to dissociate hydrogen and oxygen in the water molecule. Similar to the thermochemical hydrogen process, the water electrolysis is advantageously used when the electrical power ( $118.5\text{MJ}/\text{kgH}_2$ ) is provided by a renewable source.
Photo-electrochemical hydrogen	Hydrogen is obtained by means of the photoelectrolysis process which converts solar energy directly to chemical energy in the form of hydrogen. This process is very interesting since it has no pollutant emissions and employs a renewable energy source. Nevertheless, further improvements of the components need to be made in order to establish this technology.
Biological hydrogen	The biological hydrogen production follows four different pathways : photolytic (direct water splitting), photosynthetic bacterial (solar-aided organic decomposition), dark fermentative (organic decomposition) and microbial-aided electrolysis (electric power aided organic decomposition).

## HYDROGEN AS ENERGY CARRIER AND STORAGE

Hydrogen will join electricity in the 21<sup>st</sup> century as a primary energy carrier in the sustainable energy future (Dragica and Milica, 2003). Meanwhile, fossil fuels may serve as a transitional resource. Although hydrogen is generally considered to be a clean fuel, it is important to recognize that the steps involved in producing it may have negative impacts on the environment in some cases. For instance,  $108.7\text{kg}$  of hydrogen can be produced from  $1\text{m}^3$  of water by electrolysis using electricity and the energy of this amount of hydrogen is equivalent to that of  $422\text{L}$  of gasoline (Midilli, Ay and

Rosen, 2005). The comparison between hydrogen and other fuel as energy carrier is illustrated in Figure 2. Usually, hydrogen is stored as compressed gas or liquid form. Pressurized hydrogen technology relies on high materials permeability to hydrogen and to their mechanical stability under pressure. Currently steel tanks can store hydrogen at 200-250 bar but present very low ratio of stored hydrogen per unit weight. Storage capability increase with higher pressures but stronger materials are then required. In order to reach higher storage capability, higher pressures are required in the range of 700 bar with the unavoidable auxiliary energy requirements for the compression (Ioannis and Andreas, 2009). Compare to other gases such as Helium and Methane, hydrogen gas has lower density and consequently it requires higher compression energy (Refer to Figure 3).

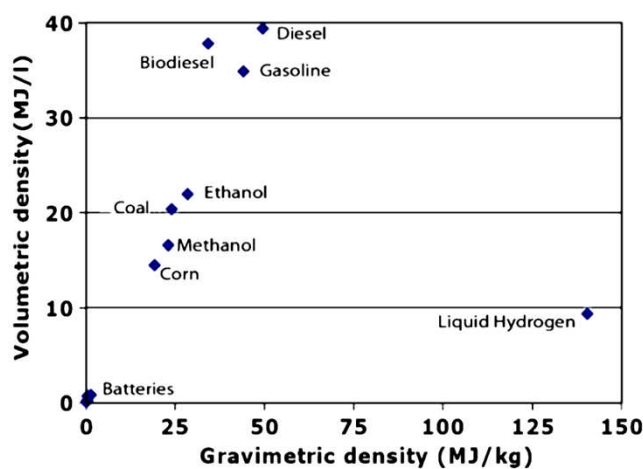


Figure 2: Caloric energy density of batteries and liquid fuels (Michael, 2009).

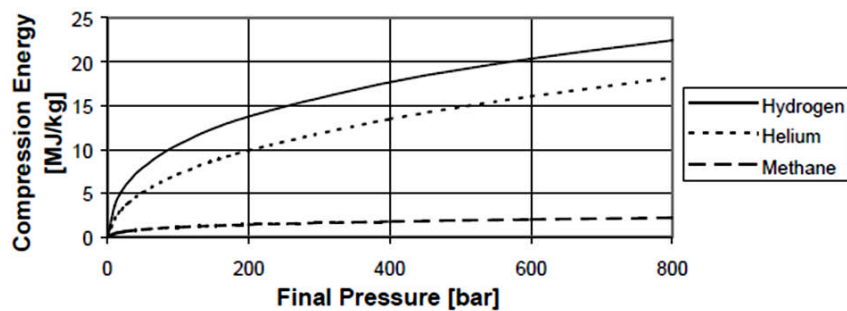


Figure 3: Adiabatic compression work for hydrogen, helium, and methane (Baldur and Ulf, 2010)

### HYDROGEN ECONOMY AND CONSTRAINTS

Sustainability is solely an inherent property of natural ecosystems, in which there is mass and energy balance. It is misleading to believe that a resource such as a crop is sustainable only because it is renewable. Many crops used for human consumption are renewable only with a large input of resources. Hence, it can be safely stated that human sustainability is possible only when it follows natural laws of mass and energy balance,

and it, therefore, an extremely complex issue. The reasons for this complexity are clearly owing to its direct connections to the natural systems of the planet – air, water, soil and sunlight – that sustain and make all life possible (Pereira, 2009). With the environmental concern, sustainable Hydrogen production is far important than the Hydrogen fuel utilisation. For the pure Hydrogen economy, production of Hydrogen gas must come from renewable sources rather than fossil fuels in order to stop releasing carbon into the atmosphere. The conversion of renewable sources must generate sufficient electric energy to split Hydrogen from water molecules without various gas emissions such as CO<sub>x</sub>, SO<sub>x</sub> and NO<sub>x</sub> and at the same time maintain the cost effectiveness the key to achieving the hydrogen economy.

The development of a hydrogen economy can have many benefits for the environment. It could play a role in reducing global warming and air quality problems in and around major cities. For the hydrogen economy to come to fruition, there are many obstacles that need to be overcome. The most prevalent roadblock is the current lack of an infrastructure to support a hydrogen economy. Hydrogen production facilities need to be constructed and methods for transporting hydrogen need to be developed. Another issue is the cost of producing hydrogen. For hydrogen to be considered as an alternative to fossil fuels, production costs from renewable resources need to be substantially reduced. The cost comparison between several hydrogen production methods is listed in Table 2.

Table 2: Cost Comparison (Jamal, 2005)

Process	Hydrogen Production Cost (per kg) RM
Gas Reformation	3.59
Wind Electrolysis	9.67
Nuclear Electrolysis	4.62
PV Plate Electrolysis	23.09
CPV Electrolysis	9.92

## SOLAR HYDROGEN PRODUCTION AS ULTIMATE SOLUTION

While hydrogen can be generated using different technologies, only some of them are environmentally friendly. It is argued that hydrogen generated from water using solar energy, solar-hydrogen, is a leading candidate for a renewable and environmentally safe energy carrier (Nowotny and Sorrell, 2005). The hydrogen, associated with other elements, abounds in nature, its combustion is not polluting. It constitutes, for that, a perfect solar fuel. Taking into account the promising prospects for the fuel cells and thermal engines with hydrogen, a system of energy to hydrogen can then be proposed as replacement solution or at least complementary, of the current system of energy production. Hydrogen is produced by solar way mainly using thermal processes, photo electrochemical and electrolytic (Rachid and Sofiane, 2007). For detail solar hydrogen production path, it is summarized in Figure 4.

Recently, four solar hydrogen systems have been selected as showing sufficient promise for further research and development (Momirlan and Veziroglu, 2002):

- a. photovoltaic cells plus an electrolyzer
- b. photoelectrochemical cells with one or more semiconductor electrodes
- c. photobiological systems
- d. photodegradation systems.

Regardless, each of these approaches has limitations, and as summarised in Table 3 exhibited a limited conversion of solar energy to Hydrogen fuel.

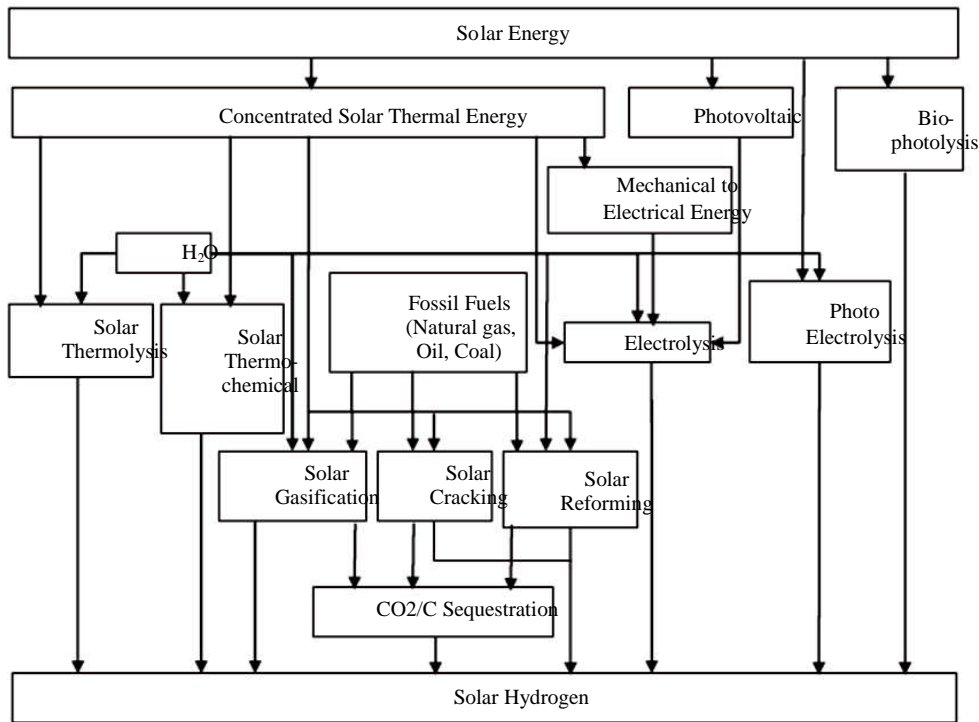


Figure 4: Solar hydrogen production (Anand and Ibrahim, 2010)

Table 3: Solar water splitting processes (Stuart, 2005)

Process	Limitations, Potential
Photosynthetic, biological and photochemical	Demonstrated efficiencies very low, generally <1% solar energy conversion
Photothermal, single step (direct)	Gas recombination limitations, high temperature material limitations, generally <1% solar energy conversion
Photothermal, multistep	Lower temperature than single step, although stepwise reaction inefficiencies lead to losses, generally <10% solar conversion
Photoelectrochemical, in & ex-situ	10-20% solar energy conversion, in-situ interfacial instability limitations
Photothermal electrochemical	Theory was unavailable, potential for >> 20% solar conversion, requires solar concentration

### CONCENTRATING SOLAR POWER (CSP) TECHNOLOGY

Solar power systems use the sun's rays – solar radiation – as a high temperature energy source to produce electricity in a thermodynamic cycle. The need for concentrating solar arises because solar radiation reaches the Earth's surface with a density ( $\text{kW/m}^2$ ) that is adequate for heating systems but not for an efficient thermodynamic cycle for producing electricity (European Commission, 2007). A wide range of concentrating

technologies exists; the most developed are divided into concentrated solar thermal (CST), concentrated photovoltaics (CPV) and concentrating photovoltaics and thermal (CPT). In general, CST is used to provide medium to high temperature renewable heat or electricity. The system use lenses or mirrors and tracking systems to focus a large area of sunlight onto a small area. The concentrated light is then used as heat or as a heat source for a conventional power plant, for example through a steam turbine or a Stirling engine (Rosli, 2010). Some of the CST technologies include Parabolic Trough, Concentrating linear Fresnel reflectors, Dish Stirling, Solar Chimney and Solar Power Tower. Same as other thermodynamic system, transformation of energy must according to the law of energy conservation. Take the solar power direct normal irradiation (DNI) as  $1000 \text{ W/m}^2$ , the relationship between inputs, output and deficiencies could be illustrated in Figure 5

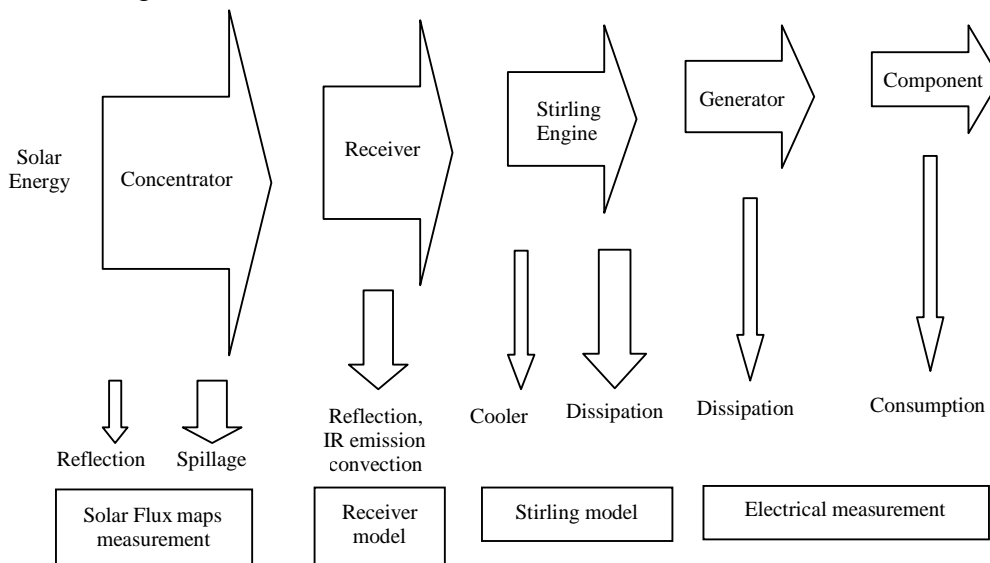


Figure 5: Solar Flux Map in the focal plane normalized to  $1000\text{W/m}^2$  (Francois, Alain and Francoise, 2009)

### PHOTOTHERMAL ELECTROCHEMICAL WATER SPLITTING

Solar electricity generated by CSP technology and followed by electrolysis of water, is a viable technical route for producing hydrogen. It can be considered as a benchmark for other routes, such as solar-driven water-splitting thermo- chemical cycles that offer the potential of energy efficient large-scale production of hydrogen (Anton and Christian, 2009). Direct thermochemical water splitting consists of heating water to a high temperature and separating the spontaneously formed hydrogen from the equilibrium mixture. Although conceptually simple, this process has been impeded by high temperature material limitations and the need to separate  $\text{H}_2$  and  $\text{O}_2$  to avoid ending up with an explosive mixture. Unfortunately, for thermal water splitting  $T > 2500 \text{ K}$  is necessary to achieve a significant degree of hydrogen dissociation. The free energy,  $\Delta G$ , of the gas reaction  $\text{H}_2\text{O} \rightarrow \text{H}_2 + 1/2 \text{ O}_2$ , does not become zero until the temperature is increased to  $4310\text{K}$  at 1 bar pressure of  $\text{H}_2\text{O}$ ,  $\text{H}_2$  and  $\text{O}_2$ . Smaller amounts of product are barely discernable at  $2000\text{K}$ . The entropy,  $\Delta S$ , driving the negative of the temperature derivative of the free energy of water, is simply too small to make direct decomposition feasible at this time. In order to attain efficient collection of solar radiation in a solar

reactor operating at the requisite 2500K, it is necessary to reach a high radiation concentration of the order 10000 times. For example a 3 MW solar tower facility consists of a field of 6450 concentrating heliostats. By directing all the heliostats to reflect the sun's rays towards a common target, a concentration ratio of only 3000times may be obtained, and to enhance this requires a secondary concentration optical system. (Stuart, 2005).

With increasing temperature, the quantitative decrease in the electrochemical potential necessary to split water to hydrogen and oxygen had been well known by the 1950's, and as early as 1980 Bockris noted from this relationship, that solar thermal energy could decrease the necessary energy for the electrolytic generation of hydrogen (Stuart, 2005). The working principle of hybrid thermal hydrogen generation or photothermal electrochemical water splitting process is illustrated in Figure 6. The model presented provides theoretical evidence that the combination of contemporary efficient multiple band-gap photovoltaic and concentrated excess sub-band-gap heat will combine into highly efficient elevated temperature solar electrolysis of Hydrogen fuel. Efficiency will be further enhanced by excess super-band-gap and non-solar sources of heat, but diminished by losses in polarization and photo-electrolysis power matching. Solar concentration can provide the high temperature and diminish the requisite surface area of efficient electrical energy conversion components, and high temperature electrolysis components are available. The theory and preliminary 50% solar water-splitting efficiencies provide evidence their combination into highly efficient solar generation of H<sub>2</sub> will be attainable.

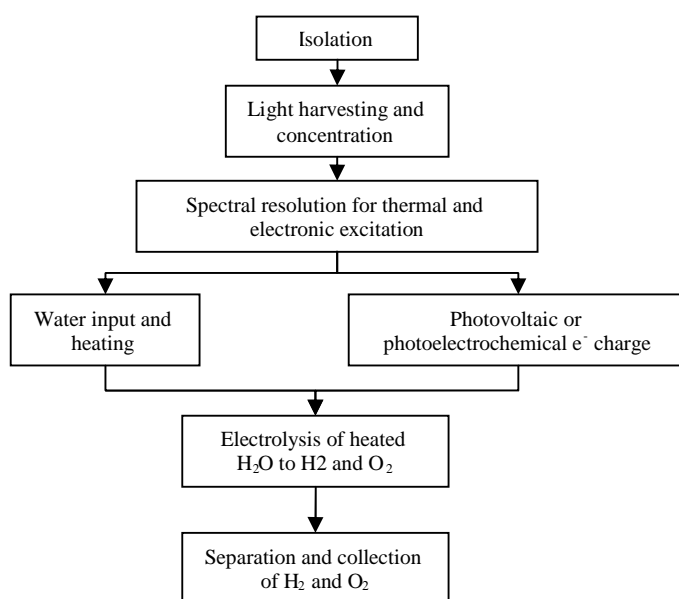


Figure 6: Process representations of solar water electrolysis improvement through excess solar heat utilization

## DESIGN OF PHOTOTHERMAL ELECTROCHEMICAL WATER SPLITTING TECHNIQUE BASED ON CST TECHNOLOGY

The thermal energy from solar energy can be utilized into two ways; low temperature and high temperature application also called concentrated solar energy. Photovoltaic,



photo electrolysis and bio photolysis are considered as low temperature application whereas solar thermolysis, solar thermochemical cycles, solar gasification, solar reforming and solar cracking are high temperature applications of concentrated solar thermal energy. Concentrating solar energy can also be utilized to produce steam and then using the power of steam electricity can be produced. The produced electricity can be utilized to produce hydrogen via electrolysis. In this communication the above method is considered in solar thermal applications only (Anand and Ibrahim, 2010).

It is a fact that hybrid electrochemical process requires less concentrating solar power but inconsistent weather changes and the photo electrode material will be one of the obstacles for large scale application. Therefore, an innovative photothermal electrochemical water splitting process with the combination of CST, Stirling generator and resonant electrolysis is proposed. In this design, the hybrid electrochemical process is altered to regenerative system as illustrated in Figure 7.

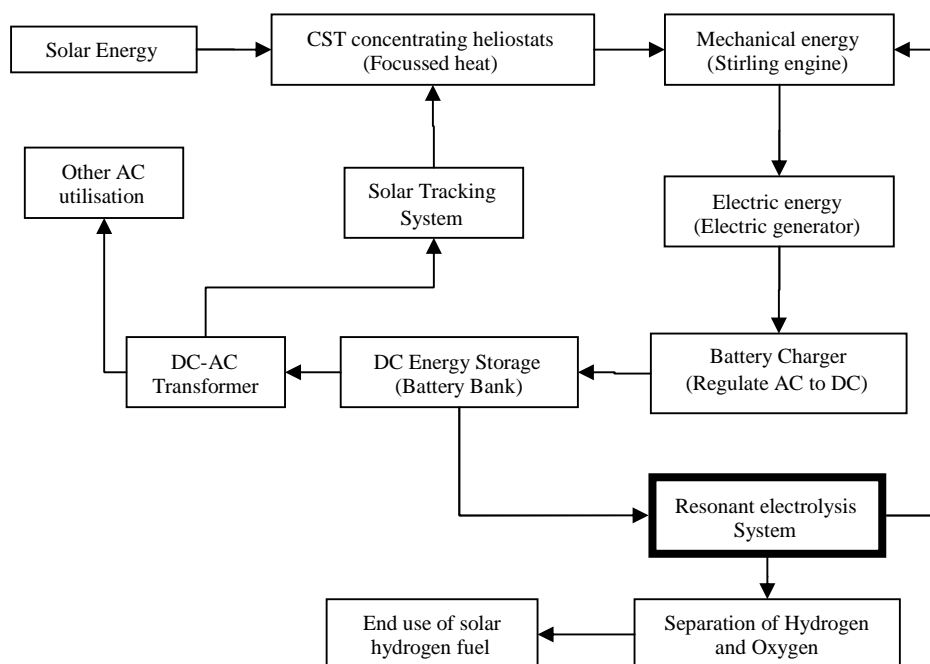


Figure 7: Design of innovative photothermal electrochemical resonant electrolysis

In this design, Dish Stirling based CST technology is a standalone solar power unit, where it requires small operating area, equipped with solar azimuth tracking system and potential to operate with wide range of focussed solar power. The energy conversion unit use innovative square rhombic drive Stirling engine with fast/slow thermal energy collector to collect and transform the light energy into heat energy. Since Stirling engine operate based on temperature different, it is less influent by weather changes as long as the focal point of the solar dish has minimum temperature variation. Instead of using expensive photo electrodes and hybrid with solar thermal energy, all solar power is converted into electric power and further dampen into DC energy storage before it is used to generate hydrogen fuel. In addition, gated pulsed high frequency resonant electrolysis system will replace the conventional DC electrolysis for higher hydrogen fuel harvesting efficiency and the small percentages of the solar hydrogen is used as regenerative Stirling internal combustion/heating for consistent operation despite of weather changes.

## INFLUENCE OF PULSE POWER SUPPLY TO WATER ELECTROLYSIS

Using a mechanical interrupted DC power supply, Bockris et al reported two phenomena in 1952. Immediately upon application of voltage to an electrochemical system, a high but short lived current spike is observed. When the applied voltage is disconnected, significant current continues to flow for a short time. They explained the first phenomenon as a double layer capacitance charging transient, followed by the electrochemical discharge of the first ionic layer, giving rise to the current, then replenished by the ionic mass transport from the bulk of the electrolyte. The second phenomenon is due to ions in the double layer facing the electrode being discharged in the absence of the externally applied field. Bockris et al and Tseung and Vassie concluded that pulsed DC may be used to improve the electrolysis process for hydrogen generation for up to twice the performance of the non pulsed DC electrolysis (Shaaban, 1994). Since then, many research and development had been conducted by various researchers and some of the achievement in summarised in Table 4. For comparison, the main different between conventional electrolysis and pulsed electrolysis is listed in Table 5.

Table 4: Previous research and achievement in pulsed water electrolysis

Researcher	Year	Achievement
Shaaban	1994	To quantify the effect of pulsed energy and anode depolarisation on the performance of the water electrolysis process.
Matsuura and Tanikawa	2004	Pulse electric potential is applied on the surface of 1-butanol to generated controlled pulse-electron emission. The tip of an atomic force microscope (AFM) (tip-radius 20nm) was employed as a negative electrode, and a tungsten rod (dia 1mm) was positioned as a quasi-positive electrode. An electric potential of 800V and 15kHz was applied between the electrodes. The electron emission in the unsymmetrical electric field decomposed 1-butanol molecules, and hydrogen was easily extracted electrically.
Naohiro, Souzaburo, Takayuki and Osamu	2006	Use ultra-short pulsed power supply based on a static induction thyristor (SIThy) and inductive energy storage (IES) circuit. As the ultra-short pulse voltage with width of 300ns is applied to a water electrolysis bath, the voltage application is so fast neither the electric double layer nor the diffusion layer can be stably formed in the vicinity of electrodes. These differences seem to be very important for the practical and industrial application of ultra short power electrolysis since the electrolysis power can be increased without decreasing the efficiency.
Roy, Rao and Kanzius	2008	When NaCl-H <sub>2</sub> O solutions of concentrations ranging from 1 to 30% is exposed to a polarised radiofrequency beam at 13.56MHz at room temperature, it generate an intimate mixture of hydrogen and oxygen which can be ignited and burned with a steady flame.
John and Marin	2010	Producing hydrogen in situ, via an electro-catalytic membrane. this decomposes the water molecules efficiently, with low input of electric current (9V-24V) and produces hydrogen on demand. The purity of in-situ made hydrogen is between 98% and 99.99% user

Table 5: Hydrogen generation performance comparison between pulsed and conventional electrolysis (Naohiro, Souzaburo, Takayuki and Osamu, 2006)

	<b>Conventional electrolysis</b>	<b>Pulsed electrolysis</b>
1	The applied voltage is increased, the current increases so that hydrogen generation rate increases, but the efficiency compared with the ideal generation rate decreases because an electron with high energy can only reduce one hydrogen ion so that the difference between the applied voltage and the decomposition voltage is dissipated as heat. Meanwhile, current itself also increased by increasing the applied voltage, electrons which are not used for hydrogen reduction are also dissipated as heat.	Hydrogen generation rate is increased as the peak voltage is decreased. It should be noted, however that the hydrogen generation rate increases as a function of the input power. When the input power is increased by increasing the pulse frequency, the efficiency was not decreased in the case of high peak voltages and was increased in the case of low peak voltages because the energy dissipation is decreased since each electron has lower energy and the pulse waveform is sharper for low peak voltages.
2	Electric field is always present. The electrical double layer is also present and the diffusion layer always exists. The current flow is applied voltage is increased, the efficiency decreases. In the case of DC power, the power applicable for a certain volume of the electrolysis bath is therefore limited	Electric field is applied for only a very short time less than several microseconds which are much shorter than the time necessary for the formation of the constant electric double layer. The electrons gathered however are quickly transferred to the hydrogen ions for electron transfer.

In term of energy flow, energy input is required to break the covalent between H-O-H and basically no heat energy is release. Since the hydrogen and oxygen mono-atomic is unstable and need to recombine into diatomic molecule and creating covalent bond will release heat energy. Using chemical bond energy analysis and enthalpy of formation analysis, the energy comparison between mono-atomic and diatomic hydrogen production is listed in listed in Table 6. From the calculation, it is noticed that total chemical bonds energy and enthalpy of formation difference for diatomic electrolysis is roughly 242 kJ/mol. This value doesn't means the electrolysis process will only require 242.8 kJ/mol of energy input. From the chemical formula, energy input to break the O-H covalent bonding is 928kJ/mol and the heat energy output to the water substance is 685.2 kJ/mol.

For the mono- atomic case, the chemical bonds energy difference is 928kJ/mol. This is the energy input to break the O-H covalent bonding and there is no heat energy output to the water substance. During the combustion process, reaction between diatomic hydrogen and oxygen gas will only generate 242.8 kJ/mol of heat energy because 685.2 kJ/mol of energy had been used to break the H-H and O=O covalent bonding. For the combustion of mono-atomic case, no extra energy is required to break any covalent bonds and the exothermic process will generate 928 kJ/mol of heat energy, which is 3.83 times of the diatomic gas combustion output heat energy.

Table 6: Theoretical evaluation for mono-atomic and diatomic hydrogen production

Type of Analysis		Conventional Electrolysis	Resonant Electrolysis
Chemical bond analysis		<b>Diatomic H<sub>2</sub></b> H <sub>2</sub> O → H <sub>2</sub> + ½ O <sub>2</sub>	<b>Mono-atomic H</b> H <sub>2</sub> O → 2H + O
Chemical bond energy (kJ/mol)	O-H	464	
	O=O	498.4	
	H-H	436	
<b>Formula</b> $\Delta H = \sum D(\text{broken}) - \sum D(\text{formed})$		$\Delta H = 2(O-H) - 1(H-H) - 0.5(O=O)$ $= 242.8 \text{ kJ/mol}$	$\Delta H = 2(O-H) - 2(H) - (O)$ $= 928 \text{ kJ/mol}$
Enthalpy of formation analysis		<b>Diatomic H<sub>2</sub></b> H <sub>2</sub> O → H <sub>2</sub> + ½ O <sub>2</sub>	<b>Mono-atomic H</b> H <sub>2</sub> O → 2H + O
Enthalpy of formation (kJ/mol)	Water, H <sub>2</sub> O	-241.81	
	H <sub>2</sub> (g)	0	
	O <sub>2</sub> (g)	0	
	H(g)	217.97	
	O(g)	249	
<b>Formula</b> $\Delta H = \sum \Delta H(\text{products}) - \sum \Delta H(\text{reactants})$		$\Delta H = \sum \Delta H(H_2) + 0.5 \sum \Delta H(O_2) - \sum \Delta H(H_2O)$ $= 241.81 \text{ kJ/mol}$	$\Delta H = 2 \sum \Delta H(H) + \sum \Delta H(O) - \sum \Delta H(H_2O)$ $= 926.75 \text{ kJ/mol}$

In making and breaking of bonds, heat of reactions was nothing more than experimentally observable numbers. Mean that energy had been released in normal electrolysis to create bonding between H and O to form H<sub>2</sub> and O<sub>2</sub>. Therefore heat is released. If the water electrolysis could generate mono-atomic gases, no heat loss because covalent bonding only sharing and not transfer electrons. Consequently, the generation and combustion of mono-atomic hydrogen and oxygen could yield higher energy efficiency. This fact implied that the pulsed power electrolysis is a promising method in which the power application can be increased even with an increase in electrolysis efficiency.

### CONCEPT OPERATION OF RESONANT ELECTROLYSIS

Although the energy input for both DC electrolysis and resonant electrolysis is same, operation method and the electric utilisation is totally different. The methodology of resonant electrolysis is based on hydrogen fracturing principle where mono-atomic hydrogen gas is produce without any ionization process. For the conventional electrolysis, hydrogen valency electron is shared between hydrogen and oxygen bonds. Because of oxygen's attraction force is higher than the hydrogen; it will displace it

valency electron and move to cathode for deionization process. In resonant electrolysis, water is used as dielectric material between electrodes and specific frequency of electric pulse is supply to the water medium to create system resonance. As the system achieves catastrophic failure, maximum vibration force will weaken the O and H bonds while high voltage polarised electrodes will switch off the covalent bonds between O and H. As a result, the main purpose of this process is to decrease the water chemical bonds energy while restricting current flow. Figure 8 shows the schematic diagram of resonant electrolysis. The basic components are built from transformer, diode, inductor and capacitor which serve as hydrogen fracturing tube. Capacitor stores energy in the electric field between its plates, depending on the voltage across it, inductor stores energy in its magnetic field, depending on the current through it.

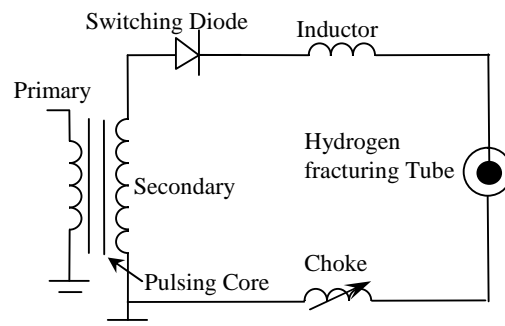


Figure 8: Basic Layout of VIC design

The operation of resonant electrolysis is complicated compare to conventional electrolysis. In simplified form, the process of resonant electrolysis could be divided into following steps:

- a. Voltage Transformation
- b. Tuning to resonant frequency
- c. Water molecule polarity and bond strength
- d. Hydrogen fracturing via high voltage pulsed polarization

For the same power supply, resonant electrolysis will amplify the pulsed voltage input via transformer. The purposes of the amplification are to increase the voltage potential polar between electrodes and minimise the circuit current flow or heat. Before the amplified voltage is reach to the electrodes, a LC circuit is use to tune the system resonant frequency. The primary coil of the transformer is subjected to 50% duty cycle pulse. Transformer pulsing coil provides a voltage step-up from the pulse generator and the output will enters the first inductor which forms an electromagnetic field. As the voltage is switched off when the pulse ends, the field collapses and produces another pulse of the same polarity i.e., another positive pulse is formed where the 50% duty cycle was terminated. Thus, a double pulse frequency is produced; however, in pulse train of unipolar pulses, there is a brief time when pulses are not present. As the amplified voltage pulse reach to inductor and capacitor, it change from gated unipolar into step charging order (Refer to Figure 9). In the hydrogen fracturing cavity, water act as dielectric material and together with the electrodes, it works as capacitor the in LC circuit. Because the voltage potential applied to the capacitor can perform work, the higher the voltage the higher the voltage potential, the more work is performed by a given capacitor.

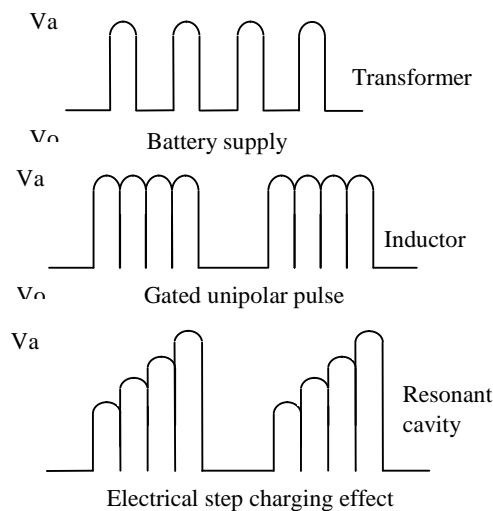


Figure 9: Change of voltage pulse pattern from voltage input to electrolysis cavity.

Based on the design and methodology, each step of the process indicate its uniqueness and some limitation. In a proper sequence and control parameters, the integrated states could perform in optimum condition and the electron leakage is inhibited. Since the process operates via voltage potential, current leakage will be the main barrier to achieve maximum yield of hydrogen gas. Refer to the previous discussion, the potential and limitation for each states of process including,

- Constant voltage
- DC pulsed
- Gated pulsed
- Electrical isolation
- Resistive material
- Resonant cavity

## CONCLUSION

Study on the fossil based and renewable based hydrogen generation process shows that the solar hydrogen is the most potential energy carrier for the future energy scheme. Recent development on CSP technology able to accumulate higher density of solar energy for the application such as photothermal electrochemical water splitting but it is not practical in the near term implementation. The proposed non-hybrid photothermal electrochemical resonant electrolysis shows the potential to lower the overall development cost and theoretical analysis also indicated that yielding mono-atomic hydrogen fuel is far more efficient than the diatomic hydrogen fuel. With proper control on each states of resonant electrolysis, the process can increase the hydrogen generation efficiency for the same energy input.

## FUTURE WORK

More detail analysis on resonant electrolysis especially the working parameters, limitation and design parameters is necessary before it can integrate with the solar Stirling Rhombic drive Stirling engine CST unit. The development of the working model is divided into two scopes – Solar dish with engine system and resonant electrolysis system. For the actual application and performance test, special water

fracturing process test equipment is designed and under development stage. The test rig is important to gather the performance data of the resonant electrolysis and its final product as integrated spark fuel injector.

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