

# **A decentralized/self-sustaining (infra-free) kitchen-system proposal with a home incinerator and Sabatier reactor-integrated waste management utility**

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## **Abstract**

This paper studies a decentralized process for solid, liquid and gas waste management in a single-person household (HH), in which the kitchen produces less or no garbage and returns valuable products to support its own system. It particularly focuses on two CO<sub>2</sub>-consuming solid waste management scenarios; (1) to use garbage as a power source with a home incinerator to run a Sabatier-reactor with an outcome of energy (methane) and water; and (2) to produce hydrogen from methane and water in order to close the lifecycle, which otherwise has to be supplied from outside. Further integration of a hydroponic unit controls the flow of excess gases to produce food, provide clean air while cooling the incinerator and improving combustion efficiency. The volume requirement of approximately 2m<sup>3</sup> could be integrated inside a prefabricated wall so that the waste management utility can be easily commercialized and installed without additional space requirements. Due to decentralization process and elimination of municipal waste collection, process and treatment infrastructure, installing the IF system could serve as a catalyst in the reduction of approximately 187 million tons of CO<sub>2</sub>-emission in the case of Japan; a 9% decrease from the 1990 emission values, where the target is set for 6% by 2012. Thus, it minimizes stress to expensive landfill area; integrating the potential of solid waste into the daily lifecycle and proposing a future kitchen system for everyday and emergency use, both in developing and industrialized countries.

*Keywords: infra-free, decentralization, resource utilization, hydroponics, home incinerator.*



## 1 Introduction

Municipal solid waste (garbage) refers to HH waste purely for living purposes and without commercial gain. They are dumped and/or brought to collection areas, which is later disposed by a city-supported social infrastructure including collection, transfer and treatment/reduction facilities through incineration, landfills, waste-to-energy facilities and land applications accompanying important financial and/or environmental issues.

The garbage in a HH is mostly produced or stored in kitchens. The influence of evolving information technologies reshape our kitchens with networked appliances like GE's self-restocking refrigerators connected to online grocery stores [1], computer controlled dishwashers or sensor technologies performing health checks improving comfort and assuring a safer environment for both young and elderly users. However, the wish for a better lifestyle results in adding new source-consuming appliances into HH and thereby, increases energy and water use, which puts more stress on our environment and centralized infrastructures. This already is a major cause of ecological decline and high life-cycle cost with utility development, maintenance, operation and replacement.

The Infra-Free (IF) research studies the concept of a decentralized lifestyle, where all type of solid and liquid waste sources produced in a HH are integrated for source reduction, reuse or recycling, treatment to process and reprocess waste to recover useful sources on-site [2]. It differs from other approaches in a sense that the proposed closed life-cycle system do not depend on environmental conditions like solar and wind power or rainwater; but on waste sources basically produced in every HH, which makes it universal.

IF describes the effective management of waste management cycle as (a) reducing the amount of sources to supply one HH, and (b) reducing the amount of waste sources leaving from a single HH. This paper will analyze likely limitations for scenario (b) with a special focus on solid waste management.

## 2 Solid waste management

IF projects an increase of approximately 2.2 million tons of solid waste in 2020 in Japan, even with the population trends set to decrease in the future, the trend of increasing single or one-couple HH will produce more waste than now [3]. This paper focuses on increasing single HH, which generates 941g/ person/ day compared to a four-person HH, which is 440g/ person/ day, in which a study on solid waste reduction could lead to a new type of decentralization.

Solid wastes could be reduced with either physicochemical or biological processes. Because biological systems require certain waste composition, more time and reactor volume, we focus only on physicochemical process technologies, as shown in Table 1.

All physicochemical technologies produce directly or indirectly CO<sub>2</sub> as a by-product. For an IF scenario, two important aspects would be that:

- a) the selected technology is well-understood and widely used at a macro-scale, should be capable to process all kinds of waste and contribute to reduction of solid waste on-site (decentralization) process



- b) the by-product ( $\text{CO}_2$ ) is efficiently reduced or completely eliminated by an integrated technology which would result in source recovery for direct or indirect use at HH

Table 1: Possible physicochemical solid waste process technologies for households.

Technology	Items technology can process	Post-process products
Incineration	Any kind of waste	Ash, flue gases, heat, $\text{CO}_2$ , water
Indirect Electrochemical Oxidation	Soluble organic materials	$\text{CO}_2$ , volatile organic compounds, $\text{Cl}_2$ , $\text{HCl}$
Pyrolysis Process	Mixed solid waste	Solids, $\text{CO}_2$ , $\text{H}_2\text{O}$ , $\text{CH}_4$
Gasification	High-heat value materials	Energy, Effluent, Ash
Supercritical $\text{H}_2\text{O}$ (Water) Oxidation	Puree, ~10% organic, ~3% inorganic, ~15% solids	Organic free oxides, $\text{CO}_2$ oxides, $\text{N}_2$ , $\text{N}_2\text{O}$
Lyophilization	Feces and biomass	Water, dry waste
Hydrogen-Peroxide ( $\text{H}_2\text{O}_2$ ) Oxidation	Paper, plastics, human waste, inedible biomass	$\text{CO}_2$ , ash, energy from steam
Plasma Arc Incineration	Combustibles	$\text{CO}_2$ , nitrates, $\text{NO}_x$
Carbon Activation	Cellulosic waste	Active Carbon, energy

Because of the capability in treating any kind of solid waste, we focus on ‘incineration’ technology to study further in a compact scale for HH. The latest material and filter technologies may enable to build home incinerators. Thereby we will try to eliminate the emission of waste carbon content (which is the case of both incineration facilities and even, mobile small-scale incinerators used in rural areas to reduce the amount of agricultural waste) by further study using  $\text{CO}_2$  with a Sabatier reactor in HH to recover sources; in form of energy or water.

## 2.1 Home incinerator

‘Home incinerators’ have not been studied in detail before. The main reason could be the control of off-gases, danger of using a combustor at home or convenience of solid waste treatment facilities. There is only one patent (US6422159) about the proposal of a home incinerator using a combustion vessel, a base trap and an afterburner [4], where the garbage is burned and  $\text{CO}_2$  is released into the atmosphere, similar to an incineration facility. Extracting the energy of garbage for heating and power in HH level could conserve commercial fuels while reducing carbon gases released into the atmosphere and saving limited landfill areas; especially for high-density cities like Tokyo.

It is essential that the house incinerator operates at elevated high temperatures; high enough to combust toxic wastes, but not too high to produce



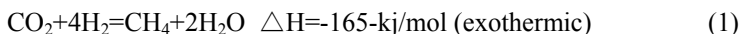
flue gases or flu ash- with a clean fuel required for start up and shut down. Such an incinerator would require about 200W of continuous electrical power and about 600W when starting up for a two-hour slow-burning process with a total energy use of about 550 W. A low-mass compact design could improve the combustion efficiency with lower energy input. We will assume that the system will use 0.5kWh/day.

For most efficiency, garbage has to be dry before burning. A separate feeding gate with a rotating chamber similar to a towel drying unit could recover water from organic wastes with high water content. The rest of the dry organic waste would then be led to main combustor for incineration process. Recovered water with nutrients goes to a hydroponic plant unit located inside the kitchen, and a LED-light system adjusts the necessary amount of light waves for the planted seed. An in-out air inlet is also installed so that stale room air is redirected to the incinerator; pre-warmed before entering the unit and cooling incinerator surface.

The combustion of waste produces energy and heat; a well understood technology used in many different waste treatment facilities. In Denmark, incinerating 1ton of waste produces approximately 2MWh district heating and 0.67MWh electricity [5]. Garbage contains the same mass fraction of carbon as CO<sub>2</sub> itself, which is 27%, so incineration of one kilogram of HH garbage will produce one kilogram of CO<sub>2</sub>. However, the excess air will not be pure enough for the Sabatier reactor, CO<sub>2</sub> has to be separated from other gases before processing. This could be achieved with reusable membrane filters containing specialized polymers to increase CO<sub>2</sub> solubility. At temperatures above 250°C, conversion rates are about 90% [6]. Watanabe states the amount of garbage fuel as 85% [7]. This would result in 720g/CO<sub>2</sub> per day for a single-HH. The calorific value of waste is 10.5MJ/kg on average [5]. The recovery of heat passing through a steam turbine could theoretically produce 2.1kWh/day.

## 2.2 The sabatier reactor

The Sabatier process is a moderately exothermic reaction, which involves the catalytic activation of CO<sub>2</sub> in the presence of hydrogen at elevated temperatures to produce methane and water, as shown in eqn (1). It is thermodynamically stable without the power requirement to maintain its temperature.



The reactor is not bigger than a small lightweight steel cylinder with mixing chamber and a chamber filled with nickel catalyst. The reaction is exothermic and once started, it will maintain itself at about 573°K; however, an electrical power of 1831kJ (0.51kWh) would be required to break H-H, C and O-O molecules and start up the reaction. Fig.1 shows the conceptual outline of a home incinerator system.

The flow of Fig.1 would have a net energy output of 1.22kWh/day, 0.6L water and 14.5MJ heat. Units adding into the total weight of the kitchen are 4.85kg (excluding the hydroponics unit) and require an installation space of 1.93m<sup>3</sup> (with the hydroponics unit). Warm stale air cools the exothermic reactor to maintain the optimum temperature and supplies excess home-air as clean fuel.



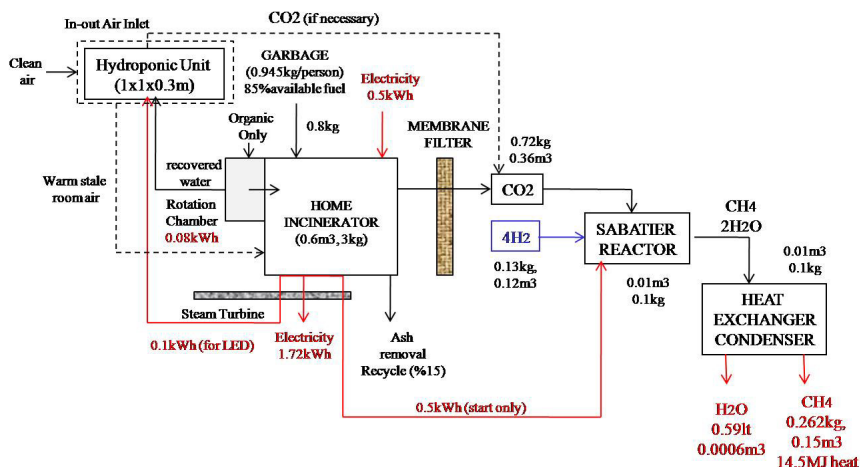


Figure 1: A Sabatier-reactor integrated home incineration unit.

### 3 At-home hydrogen production scenarios

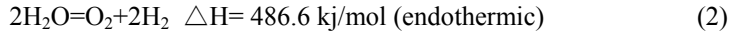
A disadvantage of system in Fig.1 is that hydrogen must be continuously supplied. For a future hydrogen economy, this system seems applicable. However, hydrogen is not suited for transportation in tanks and storage is not easy either. Because the molecular weight of hydrogen is 2.0159g/mol and  $\text{CO}_2$  is 44.0098g/mol, the reaction with 720g  $\text{CO}_2$  will need about 130g of hydrogen; thus it would require 12L of storage space even if hydrogen is compressed at 2,200psi. This would increase the space used for the system in the kitchen or possibly require installing tanks outside home. The following scenarios focus on two possible scenarios to semi- or completely close the hydrogen loop in order to eliminate storage tanks while analyzing system requirements and capability.

#### 3.1 Semi-closed hydrogen production system

Methane and water are end-products of a Sabatier system. As an initial approach, methane could be further processed using pyrolysis, which is a heating process in an enclosed device in the absence of oxygen to recover  $\text{H}_2$  and C; where the  $\text{H}_2$  could be redirected to the Sabatier reactor and left-over pyrolytic graphite can be removed. However, this would require far more energy than produced and would not completely recover all sources. Thus, methane already provides an important amount of heat energy right after the Sabatier process. So, IF-Kitchen will focus on reprocessing water as a source for hydrogen production.

The amount of water after Sabatier process is approximately 0.6L. Recovering hydrogen from water could be realized through an electrolysis process, which is well-understood, as shown in eqn (2). Although solid polymer systems have good chemical and mechanical stability, high efficiency, reduced number of moving parts and easy maintenance; we select alkaline systems to

reduce costs by a factor of four due to the costs of membrane and catalyst materials.



The hydrogen end-product could be directed to Sabatier reactor reducing the amount of supplied hydrogen to half, while released oxygen could be injected inside the combustion chamber just before the scrubber to increase efficiency of incineration process (and thereby decrease necessary energy) providing clean fuel and also to complete the reaction converting  $\text{SO}_2$  to  $\text{CO}_2$ , as shown in Fig.2.

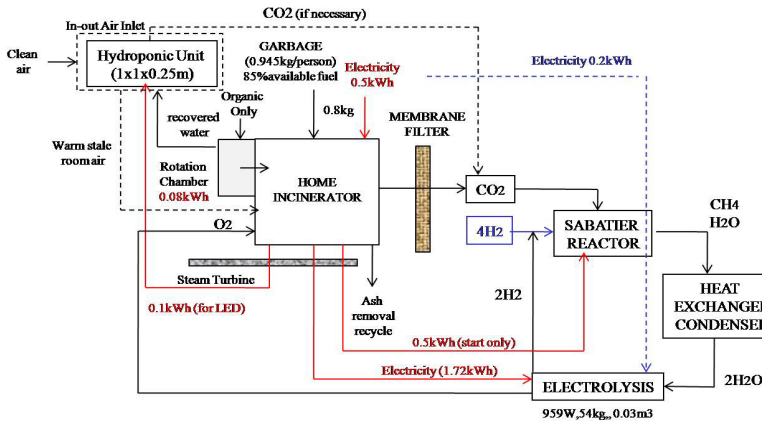
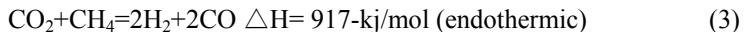


Figure 2: Semi-closed hydrogen-producing Sabatier system with electrolysis unit.

With regards to Fig.2, only 0.03m<sup>3</sup> additional volume (54kg) is required to install the electrolysis unit, which produces half of necessary hydrogen, but a continuous energy source might be necessary as the total electricity produced would be used for electrolysis system.

### 3.2 Closed hydrogen-loop home incineration system

A closed-hydrogen loop would require processing both methane and water to break the hydrogen chains they inhabit with *100% system efficiency*, where the process of methane starts with excess CO<sub>2</sub> with a reactor as shown in eqn (3).



Theoretically, this scenario of 262g of excess methane with a thermal energy capacity of 8.34MJ, produces 65g hydrogen with a thermal energy of 8.56MJ; a net gain of 3%. But the reactor itself needs a heat source; although this could be achieved through a solar mirror array, the necessary thermal heat energy to run the reactor would be about 15MJ, which would require 2.75m<sup>2</sup> of solar mirror area, considering solar intensity conditions in Japan.

At this point, the recovery of thermal heat from the incinerator surface might help to develop a compact system without additional thermal unit installation.

The size of 0.6x1x1m incinerator has four surfaces; each of 0.6m<sup>2</sup>, with a total of 2.4m<sup>2</sup>. As combustion occurs, outside air can be circulated to cool the incinerator and transfer heat through the reactor, and finally into the home regulated to necessary temperature. It would also control the access of outdoor pollutants while excess air would continue to run through the hydroponics unit, and then into the incinerator to make use of carbon content and build up common kitchen pollutants, such as formaldehyde and benzene creating an air-tight system, as shown in Fig.3.

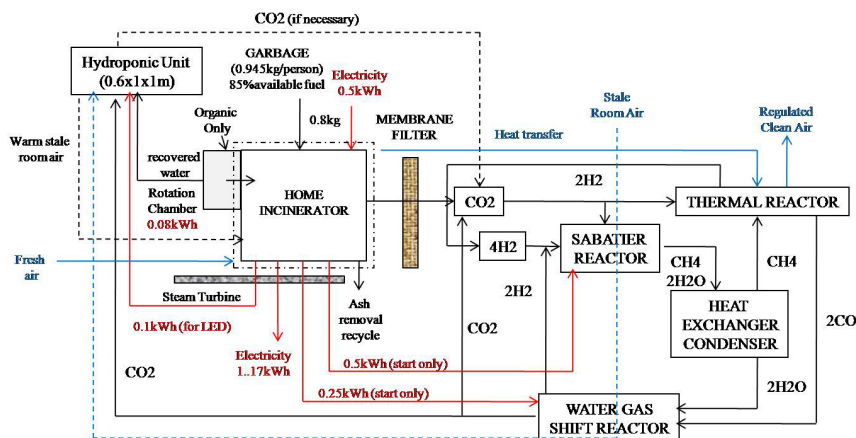
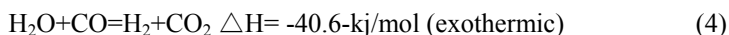


Figure 3: Closed Hydrogen-loop air-tight home incineration system.

While hydrogen is directed back to Sabatier reactor, the excess CO from eqn (3) would be fed into a water gas shift reactor with excess water, as shown in eqn (4).



The reactor would be a stainless tubular unit, 1.2cm in diameter and 30cm in length. Yongtaek and Stenger state that exiting very low CO concentrations will require very low temperatures and/or high water to CO ratios, otherwise reducing output of H<sub>2</sub> and CO<sub>2</sub> to 70% [8]. If full capacity is achieved, this reaction will produce another 65g of hydrogen and will completely close the reaction loop. Again, because the reaction is exothermic, cooling with stale room air or water could efficiently reduce heat losses. Eqn (4) will also produce 88g CO<sub>2</sub>, where half of this amount will be fed to the reactor to continue the process; while the other half would be directed to the hydroponics unit so that it could be processed by plants to produce oxygen and food, or work as a backup system for Sabatier reactor in case if there is a necessity for additional CO<sub>2</sub>, which would not be recovered from the incinerator due to the amount or contents of garbage produced. Daily energy output would be 1.17kWh. An additional 0.02m<sup>3</sup> storage space for CO<sub>2</sub> could be located below the hydroponics unit. The total necessary volume will increase by 0.05m<sup>3</sup>.

## 4 The decentralized kitchen

We next describe the installation process and possible environmental impact.

### 4.1 Installation of waste management unit

All the home incineration scenarios with Sabatier reactor, either hydrogen-supplied, semi- or totally closed require additional space to be installed inside the kitchen; from a minimum of  $1.93\text{m}^3$  to a maximum of  $2.11\text{m}^3$ , including the volume requirement for hydroponics unit. The home incinerator and hydroponics unit are the most space consuming elements, each requiring  $0.6\text{m}^3$ .

The incinerator can basically replace the space reserved for garbage boxes under the sink. Garbage can be fed through two openings (organic and others) next to the working area. The Sabatier unit is quite compact and can easily be installed behind the shelves enabling simple access and easy maintenance.

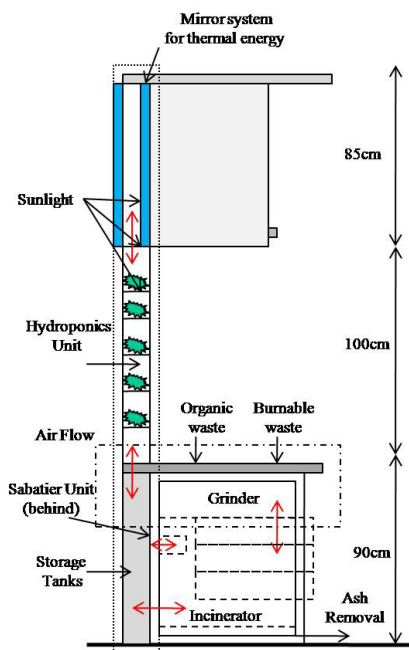


Figure 4: System sketch for prefab wall.

As shown in Fig.4, we propose a pre-fabricated wall to install the hydroponics unit located within the front wall, functioning both as a window and sub-system for waste management utility, and providing better insulation and improving plant growth conditions using stale room air. The current traditional assembly-lines of Japanese housing companies could construct prefab wall-units with a thickness of 70cm, using current production technology. Thus, the prefabricated wall unit could provide  $5\text{m}^3$  space, not only for hydroponics unit, but also for the



storage tanks of IF-Kitchen and a mirror system above for extra thermal power collection utilizing 'dead spaces' in our kitchens, which IF defines 'as areas that are located behind the working counter or overhead bins'.

## 4.2 Environmental impact

IF Kitchen would have a large impact in reducing CO<sub>2</sub> emissions, which would have otherwise be released from the social and physical solid waste infrastructural system; collection, transport, treatment and disposal. Currently, the Japanese population is 127,785,000 [9], where an average person produces 1.086kg/day as garbage [10]; a total of 50.65 million tons/year. Incinerating counts for 77% of the total; emitting 39 million tons of CO<sub>2</sub> in the atmosphere.

The ecological footprint of waste transportation could be calculated by assuming a CO<sub>2</sub> emission factor for LPG of 289.3g/km (based on the factor of low carbon content-1.6kg/l for LPG with 6km/l consumption) a total travel distance of 45km (the distance each truck delivers garbage to the nearest facility), equivalent to 13.02kg CO<sub>2</sub>/vehicle/day. Average load per truck is 4 tonnes, emissions per tonne of collected waste can be calculated as in eqn (5):

$$13.02 \div 4 = 3.255 \text{ kg CO}_2 \text{ per tonne waste} \quad (5)$$

90% of the waste is collected by garbage trucks in Tokyo, which lasts in an emission of 148.37 million tons/year. Together with incineration process, it counts for 187.37 million tons greenhouse gas emission. Japan targets a reduction in greenhouse emission by 6 percent under the Kyoto Protocol, but changes in emissions from 1990 to 2004 showed an increase of 6.5% [11]. In Fiscal year 2006, Japan emitted 1341 million metric tons; lower than the previous year but still a 5.4% increase from 1990 level. The decentralization process of HH with the IF-Kitchen could reduce CO<sub>2</sub> emissions to 1153.63 million tonnes; a 9.06% reduction from 1990 values; far below targeted levels.

## 4.3 Further requirements

Current technologies range between 50–85% depending on source composition or technology level. This would gradually reduce the final amount of available CO<sub>2</sub> and H<sub>2</sub> to 50%. The extra CO<sub>2</sub> would be recovered from incineration process but an additional H<sub>2</sub> supply would still be crucial. A 100% system efficiency would require an intensive research on hydroponics technology to reduce extra CO<sub>2</sub>. A tank could also be used to store CO<sub>2</sub> to start the reaction.

Ash is removed from the incinerator and collected on the same day with cans and bottles, which were calculated as 10% of garbage as not collected by garbage trucks in section 4.2, without lasting in any additional emission. Further studies should be conducted for the reuse of such materials for buildings or roads.

IF Kitchen could create an enormous market for housing industry all over the world. Many companies might challenge the production of a better technology, which could improve the efficiency of system in short time. District offices could offer a tax exemption for *kuminzei*-a residential tax in Japan (about \$300 per HH) collected for district services- mainly for garbage collection.



For comparison, Matsushita Electric Industrial Co Ltd offers HH fuel cells for \$10,000 with a reformer using city gas (methane) for hydrogen production [12]. A doubled cost assumption of \$20,000 for IF-Kitchen can be subsidized in 6 years with 90% *kuminzei* exemption due to the amount of garbage reduced at each HH. Thus, it would greatly reduce the stress on expensive landfill area.

## 5 Conclusion

An IF-Kitchen running a Sabatier reactor could provide energy and water in a HH. Integration of a closed-hydrogen loop could further decentralize a HH by reducing stress on physical and social solid waste management infrastructure, decreasing greenhouse emissions and improving resource integration. Using a prefab wall unit could reduce the required installation area to less than 1m<sup>3</sup>.

Further research will focus on integrations of different sub-system architectures and decentralization by integrating wastewater with solid waste management system in order to propose a completely self-sufficient IF-House.

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