Abstract

Decentralized resource management is a promising field as it has the ability to lessen impact on Earth's climate change, assist with renewable technology development, increase equity in the distribution and consumption of resources, decrease vulnerability and enable participation of local people and businesses in the supply of technologies. Alternative energy and water resources are widely researched to provide self-sufficiency in scales of single houses to communities, but are still limited to demographical, technological, economical and social factors, which vary around the globe.

Infra-Free (IF) is an academic research that seeks a synergy between relevant research fields to promote different decentralization scenarios for combined energy and water technologies with best-performance. The Infra-Free Motherboard (IF\textsuperscript{M}) is a proposal for a standardized platform, where installed technologies integrate within a household as robotic systems that evolve into a self-aware artificial platform to provide customized resource management. It addresses a multidirectional, real-time processing artificial resource management system that could develop its own skills by close interaction with the environment and the user. The system is enhanced with algorithms and dynamic systems to provide communication between different co-evolving systems that plug-in, adapt, evaluate and finally, customize themselves to dynamically changing environments due to resource availability, local needs, technology readiness and individual choices. The multidirectional real-time processing system further extends into a community application, where intelligent self-learning systems are aware of the amount and availability of resources in the whole network (community) and control the distribution between subsystems (houses) using best performance principles. Finally, this provides a dynamically transforming community that learns, adapts and redesigns itself.

In this paper; at first, we introduce the standardized IF\textsuperscript{M} and modular sub-system architecture. Next, we describe the hardware (platform) and software (self-learning process) architecture for the purpose to realize a customized real-time energy management system in a community of interconnected houses with a special focus on energy equation strategies. Next, we study a scenario to apply IF\textsuperscript{M} in a small-scale community (100 people) in Masdar in 2012; integrated with a plug-in car concept, CO\textsubscript{2} recycle, evaporative cooling and Stirling engine system. Finally, we analyze the energy equalization potential of IF\textsuperscript{M} in a computer simulation for a 6-household cluster (25 people).

Keywords: Infra-Free; decentralization; intelligent design; integrated source management; real-time energy equalization

1. Introduction

In a world of fast changing needs, individuality and growing competitiveness; spin-off technologies and iterations continue to replace older technologies faster than ever. Mobile technologies, like a 'new' PC or cell phone tends to be 'old' only in a year or two, where next-generation technologies with upgrades and add-ons provide an open-access dynamic market for providers to satisfy user needs.

Although environmental systems also follow the high-speed trend of increasing technological efficiency, installations are limited to applications, which are once build and used up to their expected lifetime due to their high capital investment and long-term cost payback. Thus, the logic of environmental systems remains not to decentralize a complete household, but to provide additional energy because of their total low efficiency compared to high rate average household resource consumption.
In this paper, we introduce IFM as a customized household resource management platform that provides flexibility of decentralization in different community scales, focusing on following topics:

**Standardization:** Integrated resource management is based on simple engineering solutions, which are combined to create more complex systems to reduce losses and improve resource productivity, but with higher costs and difficult maintenance procedures. If the IFM can provide a standardized platform like a computer motherboard, plug-in technologies could be rather simple but initiate innovation boost and cost reduction through the competition among technology suppliers that are willing to deliver standardized modules to any region in the world.

**User choices and customization:** User choices are numerous. For example, a user with high-economic income in a developing country might prefer to completely decentralize its household, while a user with low-income in a developed country might prefer to add just a single unit, or vice versa. Thus, user preferences are not only the choice of technologies, but also the resource consumption patterns that might vary due to family structure, culture, choices and other factors. In this sense, the difficulty in proposing a decentralized household is not a problem of technology; but the problem of user choice and environment. The IFM should be capable to rate different user environmental conditions, while providing simple suggestions to improve the system.

**Real-time energy equalization:** If multiple IFMs are applied in a community, the communication between these modules could provide a switch from known one-directional resource flow into a multidirectional decentralized supply network. Here, the capability of IFM network to recognize attached system components is necessary to calculate real-time energy equalization due to the needs of community.

**Embedded systems and Artificial Intelligence:** If all systems and subsystems installed on the IFM are equipped with compatible micro-systems, the combination of desired functionality could be determined by allowing the platform to self-evolve into an artificial system providing mandatory or voluntary resource conservation and/or reuse patterns depending on demography and use of sources.

Because of the wide scope of its desired behaviors, technical requirements and constraints, IF research cuts across a number of technical and research disciplines. In this paper, we describe the IFM as an integration platform creating synergies between these emerging technologies with a special focus on community application.

### 2. The IFM Platform

IFM is a proposal for an artificial control system providing slots for a set of intelligent self-organizing machines that could be integrated on a motherboard-like platform. Inspired by the idea of a PC; where the user defines the type of hardware due to factors like cost, size, available technology or personal needs; IFM offers a similar decentralization process to choose and combine between single or multiple energy, heat, water and waste management systems at user's will. Fig.1. shows the platforms' system hardware architecture, which could be installed beneath a prefabricated house, where an installation space is already available. Thus, the IFM could be build within the building skin, where each connected component- either an energy unit or even a refrigerator- would integrate within the system to reduce energy (heat) loss due to its design logic reducing entropy.

#### 2.1 System Hardware Architecture

The system is a collection of autonomous energy, water, waste and other interface subsystems, which could be provided from various suppliers with different quality and technologies, but all with plug-in capability on the IFM. Fig.2. shows the system architecture that
integrates resource management features with interior and possible exterior items controlled by a bathroom and kitchen interface. Such a system gives the possibility for action/reward system for additional user feedback.

The centralized approach to use a main processor on IFM like a PC is not feasible as it would require high speed and high processing power, wide bus bandwidth, enormous memory due to the installed energy, water and waste components on IFM that would have different working principles. The philosophy is to avoid concentration of processing power, energy and management on one processor by proposing an 'organizer' with reasonable power, communication bandwidth and memory that would use a common language between processors with internal capability, installed in each autonomous system, which are automatically recognized by a Radio-Frequency Identification (RFID) tag and have their own processors(s), unique IDs, database, sensors and actuators. They work closed-loop based on their predetermined flowchart, but may use common databases, processors, sensors and actuators to distribute the system load or to integrate their power for continuous operation in case of a failure.

2.2 Self-evolution process
As shown in Fig.3., the controller has a learning algorithm that stores user behavior and environmental data on its database to evaluate, coordinate, and perform source management functions, supporting at least one wireless communication protocol.

In order to provide a universal framework for any household on Earth, the IFM should intend to extend the flexibility, pleasure, comfort and efficiency of use as experienced by the home owner. The main deliverable of the project- the system architecture- should be independent of the implementation or choice of technologies, but should provide a network-capable universal platform with a common but abstracted language to integrate any type of user-defined scenario inside the household. For this reason, we have identified four generic use-cases:

- Attaching a new device automatically to the house's information and control system,
- Integrating new software functionality,
- Closed re-configuration,
- Resource Optimization.

The generic use-cases could apply a wide spectrum of supervised, unsupervised, semi-supervised or reinforcement learning algorithms that could accumulate and classify individual source consumption data in daily, monthly and yearly timeframes matching habits like nutrition, cooking, sleeping, cleaning and shopping. In order to understand the best learning algorithm, an experimental IFM hardware and software (HISS) have been developed, described in the following chapter.

3. IFM Experimental Unit and HISS Software
This chapter summarizes HISS (House-oriented Intelligent System Software) that has been developed to apply on the IFM experimental unit, which is a collaborative research between the University of Tokyo and Sekisui Kagaku Group. The purpose is to increase user awareness by monitoring resource consumption patterns inside a household and study algorithms that let the system to provide mandatory or voluntary resource management suggestions that matches user's lifestyle and environmental conditions.

3.1 IFM Experimental Unit
Fig.4. shows the IFM unit installed at the author's home; not only to monitor electricity, but also gas and water consumption inside a single-person household.

In order to run the system, the existing gas meter had to be replaced with a pulse unit (provided by Tokyo Gas) that has wireless data transmission capability. Thus, water monitoring also required the installation of a sensor on the water meter. The costs are ¥34,700 and ¥45,000–105,000 respectively. Electricity is monitored after attaching small mobile sensors on the fuse box. Resource consumption information is updated every ten seconds and transmitted wirelessly to the organizer (Core-I), which is the brain of the system- via I-Main- that further transfers the data to the main server or...
to user interface. A mobile device called i-tap is also capable to wirelessly communicate with Core-I, where any single electrical household appliance is monitored for more accurate data at a cost of ¥6,200 per unit.

The Core-I runs on a SH4ADSP/300Mhz main board with a PX270 CPU and 64M RAM. For minimal design purposes, there is no hard disk on Core-I while the data is backed-up on the main server, or on an USB. Current installation costs for IF system is about ¥200,000–300,000, while similar monitoring systems in overseas, if integrated, would cost about ¥600,000–800,000. Here, an important concern is to lower the cost in order to speed up payback time. For this purpose, our further research aims to integrate I-Main and Core-I into one unit to lower the costs down by half for a short-term payback, described in 3).

The unit is planned to be finalized by March 2011.

3.2 HISS Simulator

HISS simulator is written in C on Linux to run on the IFM that applies a machine learning process to observe and learn from every interaction between the user and resource consumption. Fig.5. shows the current user interface. The latest simulator version provided passive heating and cooling suggestions, detailed cost calculations for heating and cooling a specific room, electricity plan recommendations, and a savings and useless energy/money consumption indicator that were summarized in 3).

Currently, the HISS is upgraded to be connected with the IFM experimental unit and trained with two machine learning algorithms; artificial neural networks and decision trees. Here, we aim to understand the mathematical logic behind water use in different households and provide an algorithm, which would eliminate the need of installing more sensors inside the household but recognize water use patterns automatically, as shown in Fig.6.

4. The IFM Community

Fig.7. shows the main concept of IFM community that is to switch source distribution from one-directional flow into a multidirectional supply supported by a real-time processing system depending on installed technology and related information exchange between platforms.

4.1 Real-Time Energy Equalization

Fig.8. shows the architecture of IFM in a community, where a variety of subsystems and plug-ins could be embedded. The IFM would then recognize these installations, exchange information with the other IFMs in the community and provide best resource management based on predicted needs.

On the IFM, each device is recognized as an object with encapsulated inside operation/control, static memory and local energy storage that establishes a network through flows and cycles. Here, a flow is defined as the interaction between objects. This could be an airflow coming from an air conditioner into the room, or a water flow through a pipe from a hot water tank to a cold water tank. A cycle is a group of objects and flows that form a closed loop as in the example of batteries and a device; this can be a cycle with two
objects and a flow. The properties of these elements were reported in detail in\(^6\). The principal rule is that energy takes the shortest and most simple way which further determines energy equation depending on members of community at home at a specific time and connected devices, which proposes a new type of real-time neighborhood.

### 4.2 Active Environmental Transformation

Based on the active control of all actuators and applications, the whole community built on IF\(^M\) concept could be seen as an 'artificial organism' that transforms to keep the resource flow in a steady fluency. This means that house could transform its purpose over day by switching the IF\(^M\) function over day and year due to source availability and individual needs. In order to counterbalance production and consumption in an IF\(^M\) community, we propose three basic strategies, as shown in Fig.9.

![Fig.9. Scheme of Energy Equation in an IF\(^M\) Community](image)

- **Instant Equation**: As a preliminary process of energy equation in IF\(^M\), the controller routes subsystems and applications to archive a high ratio directly interconnected energy counterbalance.
- **Metabolic Delay**: Due to heights of consumption and production occurring in IF\(^M\), a constant 100% instant equation will not be possible. Therefore the controller manages energy conversion to be delayed over time.
- **Turbo Intervention**: Sometimes unexpected patterns or actions of IF\(^M\) inhabitants are likely to cause sudden height of energy generated or consumed, which could boost the energy of the 'Turbo Intervention System', that is an insurance against a sudden stand-still of the real time processing energy equation.

### 4.3 Future IF\(^M\) Community

Today, environments are created by overlaying different functions and structures that are supposed to create communication, social equation, complex non-monotonic spaces and short ways. IF\(^M\) real time energy equation proposes a new and impacting component to community environmental overlay.

As outlined in Fig.8., IF\(^M\) offers the possibility to connect or to plug-in different subsystems. Because every function has its own specific time- and user-related pattern of energy production and consumption; single-person units, family units, condominiums, home offices, offices, cars, enterprises, factories, schools and kindergartens, the energy equation strategies in section 4.2 could support all possible equations combinations in a functional IF\(^M\) overlay.

### 4.4 Cost

Total predicted costs for a single IF\(^M\) is about $30,000, while we assume that standardization could reduce the cost by a factor of three in five years, following a similar trend in related industries\(^5\).

### 5. The IF\(^M\) Masdar Community

In this section, we focus on a possible decentralized community scenario of 100 people; 4 clusters of 6 houses each, located in the Masdar city, Abu Dhabi. The Masdar Initiative is launched as a global cooperative platform for energy security, climate change and sustainable human development, which we aim to contribute by applying source integration capability of IF\(^M\) for community decentralization.

In 2012, the Urban Planning Council of Abu Dhabi forecasts 1,300,000 residents in 251,000 residential units with 12,817 Gross MW peak electricity demand and 831 MIGD/day peak water demand; lasting in 51kW/day energy and 1500lt/day water per household\(^9\). In the following sections, we introduce possible resources and plug-ins for a future IF\(^M\) community.

#### 5.1 Plug-in Car

Although Masdar city is planned as a car-free environment, the automobile remains to be the major transportation vehicle in the region. We also assume that cars will run on traditional internal combustion engines because of the economical infrastructure of UAE as a worldwide major gasoline provider. In such an engine, only about a quarter of total energy from gasoline is used to run the car, while 40 percent is lost in exhaust heat and 30 percent is lost through cooling the engine; a 70% lost in total available energy.

Current waste heat recovery from car engines focuses on using turbo-compounding and direct thermal-to-electric conversion (thermoelectric) to support electrical car devices while reducing fuel consumption\(^8\). The U.S. Department of Energy researches turbo-compound car engines for waste heat recovery to produce 10kW of additional power by 2010\(^9\). However, it is not possible to harness stable power as the excess heat changes due to the speed and type of the car. We calculate 15kW of exhaust heat during city driving and 800W for a cruise at 100km/h. In\(^8\), it is suggested that thermoelectric elements such as thallium and tellurium could interact on a quantum-
mechanical level reaching a rate of 1.5, which is a patent-pending technology and will be tested by BMW in 2009\(^{19}\). We will assume that a 20km/day drive could theoretically produce 2.4kWh and be stored on a 4kWh Li-Ion rechargeable battery with IF\(^M\) plug-in capability by 2012, which would eliminate the need of an extra battery at household.

5.2 CO\(_2\) Recycle and Water

An average car would produce 166gr/CO\(_2\)/km\(^{11}\). The IF\(^M\) community, with two cars per household would produce 160kg/CO\(_2\)/day with an average driving distance of 20km/day; 58.4 ton/year.

At 365ppm of CO\(_2\) in the air, 1m\(^3\) (40moles) of air contains 0.015 moles of CO\(_2\). We propose that the amount of CO\(_2\) in a cubic meter of air could be extracted from the air compansate for an equivalent heat released in a car combustion engine resulting in the emission of the same 0.015 moles of CO\(_2\). Removal and recycle of CO\(_2\) from 1m\(^3\) air would neutralize carbon emissions of 10kJ from gasoline.

The process of extracting CO\(_2\) from a natural airflow is akin to a windmill\(^{12}\), which could be rated by energy flux per unit area. For comparison, a windmill of 10m/s would have an energy flux of 600W/m\(^2\). Solar power has similar rates, while biomass growth rates only 3W/m\(^2\). The equivalent CO\(_2\) flux through the same area could correspond to 100,000W/m\(^2\). In order to increase the natural air flux and reduce energy consumption in a dry climate, water could be pumped to the top, which cools the air by evaporation. The dense cold air could cause a natural downdraft inside the tower, with a potential eight times larger than of water that has to be pumped up. A similar idea to harness kinetic energy from air has been proposed in Negev desert, but not built\(^{13}\).

Theoretically, the captured CO\(_2\) could be turned into a useful source rather than pumped into the Earth. In case of UAE, the captured CO\(_2\) could also be pumped into particularly late in the life of an oil reservoir to mobilize oil for enhanced oil recovery. Other studies in reclaiming bio fuel from CO\(_2\) using algae\(^{14}\) or directly into fuel\(^{15}\) are candidate technologies under improvement, but not considered in this paper. Here, we propose to focus on a well-know processes using sodium and calcium hydroxide that are abundant in Abu Dhabi area. We aim end-products as shown in Eq.1 and 2 to provide an economical income from the recycle process that could payback the system or provide budget for additional green energy purchase. However, we note that other environmentally acceptable sorbents should be explored.

\[
2\text{NaOH}+\text{CO}_2=\text{Na}_2\text{CO}_3+\text{H}_2\text{O} \quad (\text{Eq.1})
\]

\[
\text{CO}_2+\text{Ca(OH)}_2=\text{CaCO}_3+\text{H}_2\text{O} \quad (\text{Eq.2})
\]

Eq.1 lasts in the production of sodium carbonate, while Eq.2 produces calcium carbonate. Both reactions produce an amount of 2750lt/water per household, which is about two times the amount of necessary amount. From Eq.2, 98.7ton calcium hydroxide would produce 134.5ton calcium carbonate for use in construction industry. This could last in a net community profit of $23,300/year. Thus, the system could be integrated with the IF\(^M\) water circulation architecture to transfer excess heat from the CO\(_2\) tower to evaportive cooler, described in 5.4.

Although the size of the absorber system is much more uncertain; we calculate 1m\(^3\)/person for a 6.6kg/hour-CO\(_2\)/person capacity. Based on the cost of forced draft water/air heat exchangers\(^{16}\), a rough estimate suggests that the capital cost for each kg/hour-CO\(_2\) is $250. Pumping cold water to the top could increase airflow speed and generate extra electricity, but we will discuss this in another paper. Thus, Eq.2 is exothermic, which would release 96kJ/mol-C; an additional 470GJ/year heat.

5.3 Waste

UAE has one of the world’s highest levels of domestic waste; an average annual of 730kg in Abu Dhabi and 725kg in Dubai\(^{17}\). The causes of high levels of garbage could be high speed economic growth of industry, tourism and retail services, rapid population growth and immigration, lack of environmental awareness, attitude and policies.

A proposed solution is the installation of a ‘home garbage incinerator’, which could make use of excess heat from incineration with a calorific value of 10.5MJ/kg\(^{18}\). By assuming that 85% of garbage could be incinerated on-site, an additional 156GJ/year excess heat could be available. The IF\(^M\) would then manage heat cycle to necessary slots to provide and produce energy on necessity. The left-over ash could be mixed with CaCO\(_3\) as a construction material.

5.4 Cooling

Cooling counts for approximately 60% energy of an average UAE household. In this paper, we propose ‘evaporative cooling’ technology that would use only a fraction of the energy of traditional air conditioners. However, high temperature and humidity conditions would decrease the capability of cooling. Therefore, as

![Fig.10. Schematic of Two-stage Evaporative Cooling](image-url)
shown in Fig.10., we propose a two-stage evaporative cooler; where the first stage pre-cools warm air without adding humidity by passing inside a heat exchanger that is cooled by the evaporation outside\textsuperscript{19}. The second stage passes air through a water-soaked pad to pick up the humidity and cool the air, which could reduce energy consumption by 60 to 75% and make direct use of captured excess heat.

5.5 Heat and Electricity

Excess heat described in section 5.2 and 5.3 could be combined with a closed-cycle regenerative heat engine could provide mechanical or electrical power for a number of applications. Various technologies are under research\textsuperscript{20,21}. The Los Alamos National Laboratory developed a Stirling Engine (SE) with a capacity of 4,400m\textsuperscript{3}/day; converting heat into intense acoustic power in a device that compromises only of pipes and heat exchangers without moving parts\textsuperscript{22}. It has a high efficiency of electricity (30%) and heat (60%) production that could make residential application feasible.

Solar conditions in the region enable a power production of 5-6kW for each 1KW panel installed. Next, we will analyze a scenario of how the IF\textsuperscript{M} could contribute in organizing an efficient electricity and heat circulation between houses.

6. IF\textsuperscript{M} Scenario

In order to analyze the potential of the IF\textsuperscript{M}, a simulation code is written in Matlab environment. The daily life cycles of 6 families (with and without children) are simulated under some reasonable assumptions. In this section details of this simulation and resulting graphs are explained.

6.1 Initial Conditions

- Population of households is 2, 4, 4, 4, 5, 6; the first family (2 people) has no kids, but other families have 2, 2, 2, 3, 4 kids respectively.
- Each household has 2 cars that could be charged during cruise, as described in section 5.1. Men have three randomly chosen ways to go to office while women are considered to drive 1km/day at least and 20km/day at most.
- Each house has a 4kW solar panel. They work between 07:00-18:00 as a subsidiary power source and car batteries (max. 4kW) join the system whenever cars at back at home.
- Each house has a garbage incinerator providing 10.5MJ/kg heat with a waste production of 1.5kg/day (2 people), 2.5kg/day (4 people), 3kg/day (5 people) and 3.5kg/day (6 people).
- SE recovers heat from attached systems only.
- Power consumption is identical for each house, but on/off timing is random.
- Appliances are simulated in 3 main groups; 1\textsuperscript{st} group (always plugged-in) like refrigerator, 2\textsuperscript{nd} group (temporary plugged-in) like computer and 3\textsuperscript{rd} group (temporary high-consumption), such as washing machine, iron, hair dryer etc.

6.2 Randomly Defined Conditions

Daily life is full of uncertainties and is hard to predict. However there is a cycle which is more or less the same almost each passing day. Assuming the daily functions in UAE, the simulation defines random values given in an interval, for the following events at each household:
- Sleep (fixed, 00:00-06:00)
- Wake Up (between 06:00 and 07:00)
- Leaving home (for men and kids, between 07:00 and 08:00; for women, between 11:00-13:00)
- Returning home (for women, between 14:00-17:00; for men, between 18:00-20:00; for kids, between 15:00-16:00)
- Sleeping time (between 22:00 and 24:00)

6.3 Simulation Steps

Random time assignment for user data starts the simulation from 00:00, where IF\textsuperscript{M} checks the consumption and manages the potential depending on the priority of power sources. Solar panels are taken into account between 07:00 – 18:00, while the car batteries are plugged into into the system (once they back home) and finally, garbage incinerator works as an additional power source for the community, it runs only at night assuming that the garbage is collected during the day. In absence of one of these sources, the simulator adds other available resources.

The crucial point here is that, during the day, when some of the houses have a momentary power excess and some other houses have at the same time lack of power, then the surplus of power is used as a compensation power source. In other words, one household becomes a power source for the other one which becomes a consumer.

6.4 Results and comments

Fig.11., 12. and 13. show the simulation of three successive days of the community. The dark line shows the power level of the community when IF\textsuperscript{M} is applied, and the dashed line shows the case where there is no momentary power equilibrium.

In the beginning of the first day, shown in Fig.11., at 00:00, the car's batteries are full and for this reason...
the power level starts from 20kW. Then due to the first group electrical appliances that are always plugged in, the power level reduces to zero.

When simulation results are observed, the solid line is on the positive side of the graph approximately until 7 AM; however the dashed line is below zero before 6 AM. This means that IFM keeps the community energy balanced during more than 60 minutes. The same positive effect of IFM can be observed from 4:00 PM to 5:00 PM of the first and the third days. The IFM approach again keeps the community at balance for an extra hour. These results may give an idea about how conventional applications waste additional energy potential in big communities. Electricity storage requires space and is expensive depending on the power need of the consumers. However, managing the electricity momentarily may reduce the need of storage and plug-in car batteries effectively.

The effect of the solar panels during the day is quite obvious in graphs. The power excess can be preferably stored or sent to another consumer who needs power momentarily may reduce the need of storage and plug-in car batteries effectively.

7. Conclusion

The IFM idea holds the potential for a new type of real-time decentralized neighborhood that offers customization of various environmental plug-in technologies due to user choice on a self-managing real-time platform, which could boost IF technology development responding effectively to user needs and environmental conditions.

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