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SuperSuburb – A Future Cryo-powered Residential Community

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We put forward a visionary concept to address the complete energy delivery and consumption needs of a typical American residential community via hydricity, a balanced combination of hydrogen and superconductivity cryo-technologies. As energy consumption boundary conditions, we assume hydrogen will be used solely for transportation and seasonal load-leveling storage of electricity, whilst delivered electricity will provide all other needs, e.g., lighting, appliances and space conditioning. Baseline generation of both protons and electrons will be by nuclear power, delivery effected over a superconducting cable, refrigerated by liquid or supercritical hydrogen serving as cryogen and power delivery and storage agent.

BASIC SUPERSUBURB RESIDENTIAL UNIT ENERGY REQUIREMENTS

We assume the locale for SuperSuburb to be a large, upper middle class American residential community situated in a moderate climate such as found throughout California, the Southwest and Southern states. The monthly gas and electric consumption for a typical household to be found therein, such as that of the author, is given in Figure 1 below.

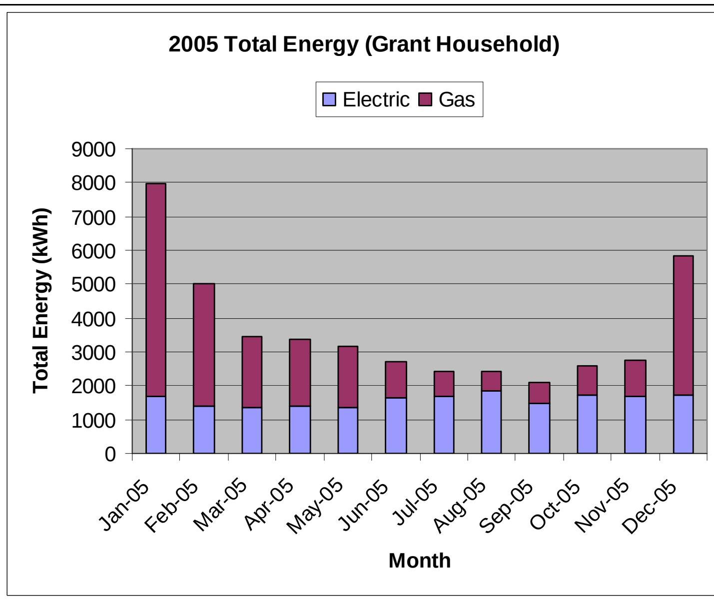

Figure 1 2005 Natural Gas and Electricity Consumption by Month for the Grant Household. A common energy unit (kWh) is employed.

Note that we have used kilowatt-hour units for gas conception in anticipation that each residence in SuperSuburb will be an "all-electric house." That is, electricity will supply all household "thermal" requirements that gas often satisfies such as heating, cooking, hot water and fabric dryers, in addition to its usual application for lighting and appliance operation. The principal domestic chemical energy used will be in the form of hydrogen replacing petroleum as the family transportation fuel of choice. However, the above chart displays a marked variation throughout the year in gas consumption strongly correlated with season, whereas electricity usage is far more uniform. Given the desire, especially for nuclear power plants, to generate baseline power at as constant a level as possible throughout the year, there is an implication that a form of electricity storage needs to be provided if electricity is to take over the task of household heating. We will assume this electricity storage is to be implemented through hydrogen generation and storage at facilities within SuperSuburb and its timely release as electricity when required. We will assume that the hydrogen independently co-generated at the nuclear plant farm will be used as baseline fuel for the personal vehicle fleet of the residents of SuperSuburb, and to serve as cryogen to support the transmission of electricity via superconductivity over the SuperCable. The statistical properties of the data displayed in Figure 1 are summarized in the following two tables:

Table I 2005 GHE Energy Consumption Statistics

Energy (kWh)	*Electricity*	*Natural Gas*	*Total*
Annual Total	18894	24882	43776
Monthly Average	1575	2073	3648
Standard Deviation	174	1747	1748
Skewness	-0.15	1.51	1.69
Kurtosis	-1.57	1.88	2.42

Table II 2005 GHE Power Requirements Based on Monthly Time Interval

Power (kW)	*Electricity*	*Natural Gas*	*Total*
Monthly Mean	2.16	2.84	4.99
Standard Deviation	0.24	2.39	2.39
Mean + STD	2.39	5.23	7.39
Mean - STD	1.92	0.45	2.60

We see that the GHE requires an average monthly power delivery of essentially 5 kW, but with a large, almost 50%, deviation. Because all SuperSuburb residential power will derive from a large nuclear facility, an attempt to "load follow" will be undesirable and impractical, yet to deliver constantly only the average will inevitably result in shortfalls during the colder seasons. Thus, a "safety factor" must be applied which is by necessity empirical, whereby enough excess electricity is generated during the warm months to store as hydrogen for reconversion to electricity and heating during the cold. Our calculations suggest a baseload rate 20% higher than the monthly mean, 6 kW per GHE, will be sufficient, and would result in a need for facilities to store a maximum energy slightly in excess of 6000 kWh per GHE which includes a 30% penalty on the round trip electricity-to-hydrogen-to-electricity (this energy need not necessarily be stored at the GHE site). The hydrogen storage infrastructure required is given in Table III.

Table III Baseline Electric Power and Energy Storage Requirements per GHE in SuperSuburb

Baseline Power (kW)	Energy Stored (kWh)	Hydrogen Mass Equivalent (kg)	Volume as Liquid (21 K, 14.7 psia) (cube edge in meters)	Volume as Gas (300 K, 2000 psia) (cube edge in meters)
5.99	6129	187	1.38	2.63

Observe that the volume per GHE to be provided for hydrogen storage for simply load-leveling monthly fluctuations is dramatically substantial. If stored as high pressure gas, the equivalent of around five 1000-gallon standard residential storage tanks would be required (if stored as liquid, a single 500-gallon tank would suffice...however, one would have to add refrigeration support). On top of the basic volume requirement, a reversible fuel cell and water supply must be added. These considerations suggest a central "utility" facility, analogous to a substation, would be more practical than on-site at the household.

HYDROGEN TRANSPORT FUEL REQUIREMENTS FOR SUPERSUBURB

We now calculate the replacement of gasoline with hydrogen throughout SuperSuburb and the delivery capacity of the SuperCable to effect its supply. As mentioned earlier, all transportation-targeted hydrogen will be produced at SuperSuburb's nuclear farm will the dual purpose of acting as cryogen to support the electricity portion of the SuperCable in transit. We will assume the demand to be more or less constant and independent of season since the fuel will be used for transportation and not heating. Table IV contains the result per GHE and Table V the number of GHEs served by one hydrogen station.

Table IV   GHE Transportation Energy Consumed

Miles/Year	DOE H_2 Mileage (kWh/mile)	H_2 Daily Mass Consumption (kg)	SuperCable H_2 Delivery Power (kW)
30,000	0.76	1.91	2.61

Table V   Number of GHEs per H_2 Station and Individual Station Capacity

US Households (2005)	Number of Stations (1998)	Households per Station	Turnover Rate (days)	H_2 Mass (kg)	Liquid "cube" (meters)	Gas "cube" (meters)
75,000,000	187,000	401	3	2298	3.2	6.1

POWER DELIVERY TO SUPERSUBURB VIA A SUPERCABLE

Table VI summarizes the total power delivery required by a SuperSuburb of 300,000 GHEs, roughly the bedroom community of a city on the scale of San Jose, California, to be delivered from

Table VI. Baseline Electric and Hydrogen Power Needs of a "San Jose" SuperSuburb of GHEs

GHE Households	Base Electric Power (MW)	Electricity to be Stored as H_2 (tonnes)	Base H_2 Power (MW)	H_2 Stations
300,000	1798	56,104	782	748

a single nuclear power plant over a liquid hydrogen-cooled superconducting cable as depicted in Figure 2 dispatching 1800 MW as electricity and 800 MWe as hydrogen chemical energy.

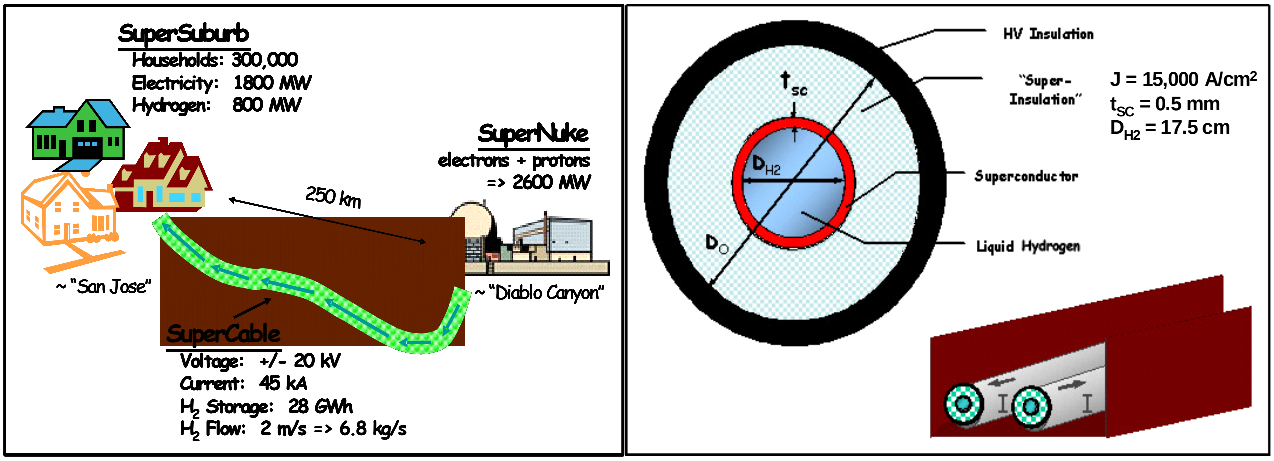

Figure 2 Conceptual depiction of SuperSuburb and its power generation and delivery system.

Table VII. SuperSuburb SuperCable Monopole Physical Parameters (See Figure 2)

Operating Current Density, J (A/cm^2)	t_{SC} (cm)	Hydrogen Flow Rate (m/s)	D_{H2} (cm)	Maximum Magnetic Field (T)
15, 000	0.05	2	17.5	0.10

It is remarkable that a layer of superconducting tape only 0.5 mm thick surrounding the liquid hydrogen transport tube 17.5 cm (nearly 7 inches) in diameter comprising an annulus of about 3 cm^2 in area, is sufficient to carry 45 kA of electric current. We assume "Generation II" HTSC tape soon to be available from several manufacturers will have operational current densities of the order 17,000 A/cm^2 at 77 K in tapes nominally 0.25 mm thick and 4 mm wide available in continuous lengths up to 800 meters. Inasmuch as the operating temperature will be around 21 K, our choice of operating current density is very conservative. About two layers of tape will be sufficient, but splices will be needed every kilometer or so and these may present a difficult issue. Table VIII below summarizes these details.

Table VIII. SuperSuburb SuperCable Monopole Minutia and Costs

HTSC Tape Parameters							
Width (mm)	Thickness (mm)	Length (m)	Total No. Tapes	Tape Req'd (km)	Approx. No. Splices	Tape C/P ($/kA×m)	HTSC Cost (M$)
4	0.25	800	~300	~80,000	~100,000	50	591

Table IX. SuperSuburb SuperCable Monopole Thermal Loss Budget Based on Specifications and Dimensions from Figure 2 and Table VII (All units in W/m)

Radiation	Flow Friction	Addenda Loss	1.0 % Ripple	Total
0.70	0.49	0.20	0.09	1.48

Table X. SuperSuburb SuperCable Monopole Refrigeration Requirements Based on Specifications and Dimensions from Figs. 2-3, Table VII and Table IX

Temperature Rise (K/km)	Total Rise for 250 km SuperCable (K)	Permissible Rise Prior to Re-Cool (K)	Total Number of Cooling Stations Required
0.045	11	1	11

Station Spacing (km)	Cooling Power per Station (kW)	Cost of Heat Uplift ($/kW)	Per Station Cost (K$)	Total Station Cost (M$)
22.25	32.9	5	164	1.85

We see from Table IX that radiation heat in-leak is the largest thermal load on the SuperCable followed by fluid (LH_2) flow friction (addenda losses are estimates of other losses, such as support thermal conduction, ohmic losses from HTSC joints (trivial), etc.). However, it is important to note that hysteretic losses from ripple go as the third power of the rms current at 360 Hz, and thus increase rapidly if filtering is inefficient. For example, if the ripple is at 3% of 45 kA, it dominates other sources and the total heat load almost triples.

Table X contains performance and cost data in support of the refrigeration infrastructure necessary to service the SuperCable. We note that the cost is almost negligible compared to that shown in Table VIII for HTSC wire (at 50 $/kA×m). Even so, under the assumptions detailed in Table XI below, these additional costs over and above conventional power delivery systems can be recovered in a reasonably short time.

Table XI. SuperSuburb SuperCable Economic Factors. Note that the Capital Equipment Costs from Tables VIII and X have been doubled to reflect that two monopoles are actually in service.

Cost of Electricity ($/kWh)	Line Losses in Conventional Transmission (%)	Annual Value of Losses on 1800 MW Transmission Line (M$)	Additional Capital Costs for HTSC and Refrigeration (M$)	FRB Discount Rate (%)	Period for ROI (Years)
0.05	5 %	39.4	1185	5.5 %	18

We have assumed throughout this analysis that converter costs for both conventional HVDC and the SuperCable would be roughly the same. Furthermore, we have assumed that the SuperCable would be permanently evacuated and have included the cost of re-pressurization (pumping) of the liquid hydrogen in the $/W calculation for heat up-lift. An additional concept deserving future consideration is one where the cryogen is liquid nitrogen and the hydrogen is co-transported as high pressure supercritical gas at 77 K.

CONCLUSIONS

We believe our preliminary calculations presented here demonstrate that the realization of SuperSuburbs can be justified on the basis of existing technologies and their costs. In particular, we examined in some detail the capitalization and subsequent return-on-investment for the Hydricity SuperCable present an attractive financial opportunity.

However, having said this, there remain other, non-technical in nature, factors that likely override these issues in the actual deployment of the SuperSuburb, or its antecedents and derivatives. Among these are the revival and acceptance of nuclear fission energy worldwide, the possible connection of observed global warming to anthropogenic-sourced emissions of carbon dioxide, and the desire to meet these with technologies least invasive and harmful to the planet ecology. Should these issues prove paramount to our global common habitat, the SuperSuburb concept can contribute to their solution.

ACKNOWEDGEMENTS

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REFERENCES

1. Program on Technology Innovation: Functional Requirements of a Hydrogen-Electric SuperGrid, Technical Update 1013204, March 2006, available on request from the auther.