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Distributed generation: remote power systems with advanced storage technologies

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Abstract

The paper discusses derived from an earlier hypothetical study of remote villiages. It considers the policy implications for communities who have their own local power resources rather than those distributed through transmission from distant sources such as dams, coal power plants or even renewables generation from wind farms, solar thermal or other resources. The issues today, post 911 and the energy crises in California, Northeast North America and Europe, signal the need for a new and different approach to energy supply(s), reliability and dissemination.

Distributed generation (DG) as explored in the earlier paper appears to be one such approach that allows for local communities to become energy self-sufficient. Along with energy conservation, efficiency, and on-site generation, local power sources provide concrete definitions and understandings for heretofore ill defined concepts such as sustainability and eco-systems. The end result for any region and nation-state are "agile energy systems" which use flexible DG, on-site generation and conservation systems meeting the needs of local communities.

Now the challenge is to demonstrate and provide economic and policy structures for implementing new advanced technologies for local communities. For institutionalizing economically viable and sound environmental technologies then new finance mechanisms must be established that better reflect the true costs of clean energy distributed in local communities. For example, the aggregation of procurement contracts for on-site solar systems is far more cost effective than for each business owner, public building or household to purchase its own separate units. Thus mass purchasing contracts that are link technologies as hybrids can dramatically reduce costs. In short public–private partnerships can implement the once costly clean energy technologies into local DG systems.

Keywords: Distributed generation energy; Environmentally sound technologies; Remote communities; Advanced technologies; Optimization and economic models

1. Introduction

Distributed generation or distributed energy systems (DG) have been promoted in various forms for many years (Lund, 2000, 2001; CEC, 2002a, b, 2003; CPA, 2002). The notion that energy must be supplied from a central grid controlled by state monopolies has given way to power generated and transmitted from "agile" energy systems which are diverse, geographical and functional (Clark and Bradshaw, 2004). Some of these new DG systems are controlled by municipalities, other local government entities, private sector firms, coordinated public sector buildings, and in some emerging cases, partnerships between the public and private sectors. In general, DG is a different market mechanism structure for nation-states.

DG has taken on a number of definitions. However, in California with the energy crisis from 2000 to 2002, one application was the use of "on-site" or sustainable power for buildings (CAA, 2001a, b; CPUC, 2002; CEC, 2002a, b; LADWP, 2002). The State undertook a program directed at "greening" public buildings. No matter what the configuration, the results tend to be same: more diverse supply of energy generation,

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separate sustainable energy systems, interconnection problems and barriers, and competition for customers.

While distributed generation systems have not been fully integrated into any state or national energy plan, a number of state governments have serious legislative initiatives under way (CAA, 2002). In light of the energy crisis in California and then the threats to energy infrastructures as a result of the 911 attacks on America, the blackouts in the Northeast USA and Southern Canada and throughout Europe in the Summer of 2003, more attention is being given to this "flexible" systems at the local level perspective for supplying reliable energy (Lund, 2001; Clark and Lund, 2001; Clark and Bradshaw, 2004). In California, to address these issues, Governor Davis' Commission for the 21st Century specifically recommended distributed generation (CPA, 2002, pp. 40–44).

This paper considers DG systems in the context of these both energy and political events. The supply of reliable energy is critical infrastructure for any society but especially in the modern electron dependent industrial nation-state. Remote communities of any kind can provide an excellent example of how distributed energy systems can operate. The analysis focuses upon a model of how remote communities must pay economic and environmental penalties for electricity, because they must import diesel as their primary fuel for electric power production, paying heavy transportation costs and potentially causing environmental damage with empty drums, leakage, and spills.

For these reasons, remote communities offer a viable niche or demonstration market where sustainable energy systems based on renewable resources and advanced energy storage technologies can compete favorably on purely economic grounds, while providing environmental benefits. These villages can also serve as a robust proving ground for systematic analysis, study, improvement, and optimization of sustainable energy systems with advanced environmental technologies.

This paper presents data, an analytical optimization of a remote power system, economic parameters (Bolinger and Wise, 2002a, b), and derived policy recommends (Clark, 2002) for a hypothetical Alaskan village (Isherwood et al., 2000). The analysis considers the potential of generating electricity from renewable energy (e.g., wind and solar), along with the possibility of using energy storage to take full advantage of the intermittent renewable sources readily available to these villages. Storage in the form of either compressed hydrogen or zinc pellets can then provide electricity from hydrogen or zinc–air fuel cells when renewable sources are intermittent or undependable.

The analytical results show a great potential to reduce fossil fuel consumption and costs by using renewable electricity generation technologies as well as advanced energy storage devices. Moreover, it is suggested that hydrogen could play a significant role as an energy carrier and for storage. Subsequent research appears to confirm these earlier conclusions (Clark and Bradshaw, 2004).

DG can offer a number of viable economic solutions. The best solution for the hypothetical Alaskan village, from a few years ago, appears to be a hybrid energy system, which can reduce consumption of diesel fuel by over 50% with annualized cost savings by over 30% by adding wind turbines to the existing diesel generators.

When energy storage devices are added (e.g., using hydrogen or fuel cells), diesel fuel consumption and costs can be reduced substantially more. With optimized energy storage, use of the diesel gensets can be reduced to almost zero, with the existing equipment only maintained for reliability and readiness. However, about one quarter of the original diesel consumption is still used for heating purposes. Throughout the term 'diesel' is used to encompass the fuel, often called 'heating or fuel oil', of similar or identical properties.

Above all, the key to implementation of new environmentally sound technologies is the ability to reduce costs. This was exactly how diesel and other conventional fuels and technlogies became the standards today. Cost reduction is historically often government driven in both government regulations and procurement policies. The same is true today for clean, green, renewable technologies as the State of California discovered from 2002 to 2004. The finance battle, however, is still being waged today through public–private partnerships in both sectors create and then implement public policy for distributed generation systems.

2. Background

The decline of research and development (R&D) funding, especially for environmental and technologies (Clark, 1997, 2000) has lead to the need to optimize the use of new advanced technologies in order to maximize energy efficiencies, reduce environmental impact on climate and pollution, while being cost competitive with existing technologies. We argue that the introduction of new technologies, when seen within a systems context, need to be analyzed and planned for implementation in local communities. An earlier paper focused on the overall optimal planning for remote villages (Isherwood et al., 2000).

The United States has seen its research and development (R&D) funding as a portion of real GDP decline over 5 years. Clark (1997) examined this issue for the US as part of a study for the United Nations on *Publicly funded research and development on environmentally sound technologies*, with a special focus on how to transfer or diffuse such technologies developed in the

US to developing nations. The results of the study were instructive and formed a part of a 10-nation Report for the UN. The California energy crisis provided a unique opportunity to apply new advanced technologies as part of the solutions (Clark, 2001).

Studies of R&D characterize the demands of industry as being short-term and often too narrow to satisfy markets and shareholder pressures. Whereas the universities are long-term oriented in their research programs, in part due to the time needed for graduate students to finish their dissertations (note the time frame is about 5–8 years, often the time needed for students to conduct research, write the thesis and publish it). Laboratories have a 2–5 years time frame, which places them closer to the commercialization time frame of industry which is within months of the funding, and certainly not more than a year or two, before R&D must see products in the marketplace. These time frames are important because industry or the market rarely funds R&D that takes over 2–3 years before it is commercialized. Competition and certainly shareholders demand a far quicker return on the R&D investment than the more long-term laboratory and university R&D cycle.

Therefore, much of the long-term R&D in the US must be publicly funded. Much of the George W. Bush administration "Energy Budget" proposed in 2004 (2005 FY) has large sums of funding for energy R&D, including DG and new technologies such as fuel cells, storage devices and hydrogen. Depending on how one counts R&D budgets, and aside from the US Department of Energy with its 11+ laboratories and over $16 billion budget for their operation. There are almost 720 other public laboratories in other federal departments and agencies with another $50 billion of funding.

The current American Congressional economic ideology sees government environmental policy turned into research programs through environmental R&D. In other words, environmentally sound technologies (ESTs) need to be funded by the private sector to meet the environmental policy demands of government, or environmental policies and regulations should not be implemented in the first place, since they put an undo hardship on industry. This is the essence of the American debate over the global Kyoto guidelines. Government regulations or guidelines interfere with the free market (sic) and will hinder economic development.

ESTs, in this political context, differ from other forms of research in that they are often viewed as "applied" to and meeting public policy decisions. Thus while the government can create the regulatory demand for ESTs, it places the R&D burden on the private sector or more recently on state, regional and local authorities. Hence, states and regions must increase their role in both the regulatory and funding arenas for ESTs.

Definitions of distributed generation need to be outlined. Consider the following potential definitions extrapolated from IEEE DG Committee on their IEEE web page: <http://grouper.ieee.org/groups/scc21/1547/index.html>.

- Distributed Generation (DG): electric generation facilities connected to an Area EPS (Electric Power System) through a PCC (Point of Common Coupling); a subset of Distributed Resources (DR).
  - Distributed Resources (DR): sources of electric power that are not directly connected to a bulk power transmission system. DR includes both generators and energy storage technologies.
  - Electric Power System (EPS): facilities that deliver electric power to a load. Note: this can include generation units.
  - Area Electric Power System (Area EPS): an electric power system (EPS) that serves Local EPSs. Note: typically an Area EPS that normally has primary access to public rights-of-way, priority crossing of property boundaries, etc., and is subject to regulatory oversight.
  - Local Electric Power System (Local EPS): an EPS contained entirely within a single premises or group of premises.
  - Point of Common Coupling (PCC): the point where a Local EPS is connected to an Area EPS.
  - Point of DR Connection: the point where a DR unit is electrically connected in an EPS.

3. Policy issue

Assuming the definition of DG, the policy question is clear: what is the cost of commercializing technology for DG? Without engaging in the political debate over the role in government, the basic issue often focuses upon the justification of federal or state funds for research, development and technology commercialization in terms of "job creation". Aside from the political popularity of job creation, further analysis reveals that this is not the best, and certainly not the sole, metric for success. The conclusion is that DG needs government support.

The important question is what are the policies that supported distributed energy generation? California has begun a process which begins to outline what the implications for public policy will be. First in 1999, the California Public Utility Commission (CPUC) issued an order defining distributed generation as "small scale electric generating technologies such as internal combustion engines, micro-turbines, wind turbines, photovoltaics, and fuel cells" (CPUC, 1999).

Since then the debate over distributed generation has taken on an important role as a national security issue in large part due to the issues surrounding infrastructure security from the attacks on the USA on September 11, 2001. If energy infrastructures, for example, are to be functional even in the threat of attacks then they must be less grid dependent or distributed. The model for such an infrastructure needs to include distributed energy generation (Clark, 2001). The California Energy Commission (CEC) took up this challenge formally in early 2002 when it began to draft a Strategic Plan for distributed generation in which it began to more define the field beyond technologies as: "the generation of electricity near the intended place of use." Then the plan goes on to add, "Some parties define it with size limitations, others exclude backup generation, and yet others make no distinction between generation connected to the transmission system and generation connected to the distribution system." In short, distributed generation needs definition and regulatory rules with oversight.

Some policy makers and scholars argue that job creation is the basic metric for justifying government funding. The essential problems are in defining the types of jobs (public or private sector) and determine the long-term impact. Studies have found that job creation for the public sector are often unproductive (that is, public sector temporary positions) and often generate low tax revenues. Creating high paying and sustainable jobs requires a different set of metrics to measure the successful outcome of government plans, policies, and funds.

Distributed generation can, for example, be seen as economic development. Studies of "science parks" (Clark, 2001) note that these high tech R&D centers can also be "green" or part of a sustainable development planning process (CAA, 2001b; CPA, 2002). California formed a Stationary Fuel Cell Collaborative (CSFCC, 2002) in part to push and promote the commercialization of fuel cells. Many communities have done just that with public building such as schools leading the way with new solar/photovoltaic technologies proving on-site power (LADWP, 2002; CPUC, 2002). The applications of DG have also been shown as cost effective (Bolinger and Wise, 2002a, b) especially when considering life cycle analysis and externalities (Clark and Sowell, 2002).

Saxenian (1994, 2002) among others saw the need for regional planning. Such an approach including DG at the local level (Lund, 2000; Münster, 2001) was also reflected in California state policy with the passage of the Environmental Goals Policy Report Bill (EGPR) in the fall of 2002. The first EGPR was completed in the fall of 2003; nothing like it had been in California for 26 years, included in the EGPR were sections on sustainable development and DG along with new advanced technologies tied to a range of infrastructures including transportation, water and waste.

The American economy represents one of the largest single language, culture, and political markets in the world. While the European Union intends to create a larger single market in terms of population (over 300 million) and monetary system (with the introduction of the EUC by the turn of the century), the American market will remain potent given its single political and language systems. For American businesses, historically, the domestic market proved to be their only market; or more precisely the only market that they needed. The last decade has witnessed an enormous change in that strategy. Most American businesses and industrial sectors now see their domestic markets as accounting for fewer than 50% of their revenues. The very survival of a company depends now on foreign trade.

The American economy is moving rapidly into what Drucker calls the "post-capitalist era" (1993) whereby the very definition of capitalism is changing. Capitalism is no longer defined in terms of Adam Smith as strictly dominated by the private sector, despite the political rhetoric, but are now far more collaborative between public and private sectors. In that sense, the American form of capitalism has moved far more to that form of other industrialized nations, while those countries in their need to control costs, raise federal funds to support programs, and be competitive in the marketplace, have moved to sell or privatize heretofore nationalized industries ranging from telecommunications to utility/power to rail and postal services. The new world wide definition of capitalism (Drucker, 1993; Heilbronner, 1993) into more of a "market economy" has produced enormous economic changes, some of which will not be felt for another decade or more. For some American economists and certainly observers in other industrialized nations, the new form of American capitalism is not new news.

According to Science (March 21, 1997, p. 1729), the USA funds just under 50% of its total research and development from public funds. While it is not stated, that percentage assumes that the amount does not include defense or military related R&D. In comparison to the USA, according to the Science report, Japan funds about 30% of its R&D using public funds, while Germany and the United Kingdom R&D are about at the same level as the USA in terms of publicly funded R&D compared to their overall R&D spending. With slightly more than half of the R&D funding coming from the public sector, France is the leading country, in this respect. As the article notes in commenting on the funding for R&D in France: "As laboratory budgets have stagnated or fallen in recent years, many scientists have done exactly what the government wants them to do: They have sought contracts with industry." (Science, March 21, 1997, p. 1729). This is the trend in the US as well R&D organizations seeking alliances with industry, other governmental groups and non-defense international collaborations.

Yet, the USA has seen its R&D funding as a portion of real GDP decline over the last 50 years for example in comparison to other G-7 countries (from 70.6% to 48.1%) and OECD countries (from 70.6% to 43%) by almost a factor of two (Science, March 21, 1997, p. 4), despite coordinated efforts by the science community to maintain and restore at least current levels of funding. When examining funding of R&D in the USA over the last 5 years, the figures are even more disparate. While the US percentage of GDP was 2.54% in 1994, so also was the United Kingdom and close behind were Germany at 2.33% and France at 2.38%. However, Japan and Korea exceeded the US by 2.9% and 2.6%, respectively (Science, March 21, 1997, p. 4). The trend toward among other industrialized countries for international investment in R&D continues and has significantly increased, thus challenging the US competitiveness in technology innovation and diffusion.

In the following, a more detailed analysis of the R&D budgets is made which is linked up with the Charts 1–6 of Appendix A. The figures and data contained in the Charts 1–6 are drawn from the following document: *International Plans. Policies. & Investments in Science & Technology*. US DOC, Office of Technology Policy (April, 1997).

Chart 1 gives a Grand Total of R&D spending including all areas in the USA compared to some other developed countries. Interesting is that three areas, namely Energy, Environmental Protection, Earth & Atmospheric and Defense are rendered prominent. These areas tend to be the ones that have public funds for ESTs imbedded in their budgets, while others do not. Hence the Grand Total does not reflect the total of those areas, but instead of all areas including several not listed. As demonstrated by the figures as contained in Chart 1, the USA lags behind other countries in R&D

Objective	US	Japan	Germany	France	UK	Italy	Canada
	1994	1994	1993	1993	1994	1993	1992
Grand Total	68,331	18,099	14,991	13,716	8,669	8,042	3,370
Energy	4.2	20.5	4.3	3.9	1.1	4.0	5.5
Environ. Protection	0.8	0.5	3.7	1.3	2.0	2.5	2.1
Earth & Atmosph	1.4	1.2	2.8	1.1	1.9	0.9	3.5
Defense	55.3	6.0	8.5	33.5	44.5	6.5	6.2

Chart 1. Country (year of coverage) in millions of US Dollars. Grand total includes all areas; select areas are presented herein; areas listed thus will not equal Grand Total. Source for Charts 1–6: International plans, policies, and investments in science and technology, US DOC, Office of Technology Policy (April, 1997).

Agency	Total	Life Sciences	Environmental Sciences	Engineering
Total: All Depts. & Agencies	28,161	11,609	2,690	5,629
Agriculture	1,315	1,016	12	62
Defense	4,262	322	256	2,161
Energy	3,380	269	400	674
Interior	584	115	309	100
Transportation	310	7	5	190
AID	271	217	0	0
EPA	415	114	177	122
NASA	3,682	169	797	1,552
NSF	2,219	350	471	310
TVA	34	13	1	2

Chart 2. Selected Federal research obligations by agency and field FY 1995 (millions US$). Total All Fields includes all areas; select areas are presented herein; areas listed thus will not equal Total All Fields.

Field	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Total All	7819	8153	8944	9474	10602	11286	12171	12490	13399	14043	14201
Total Life Sci.	3787	3859	4364	4502	4916	5176	5434	5842	6289	6674	6898
Envir. bio	126	126	141	147	157	168	187	202	223	260	261
Total Envir. Sci	70	749	781	873	1017	1275	1264	1304	1533	1575	1526
Atmo Sci	209	240	244	281	316	441	449	435	635	650	633
Geog	250	266	266	267	335	440	449	520	555	563	528
Ocean	219	224	250	269	294	300	198	210	207	216	214
Other	21	19	21	55	72	92	118	132	136	146	151
Engin	884	969	990	1006	1184	1102	1234	1250	1207	1325	1286

Chart 3. Federal Obligations in basic research by science, engineering field (millions US$). Total All Fields includes all areas; select areas are presented herein; areas listed thus will not equal Total All Fields.

Field	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Total All	8315	8349	8999	10163	10453	11286	12171	12490	13399	14043	14201
Total Life	2576	2606	2980	3223	3579	3660	4188	4069	4483	4676	4711
Envir. Bio	135	138	149	154	210	174	273	309	333	349	352
Total Envir.	704	733	731	734	758	899	886	904	1075	1257	1764
Atmo Sci	277	281	309	307	272	330	354	332	349	421	353
Geog	179	178	176	174	208	221	230	209	243	259	295
Ocean	179	205	178	191	198	220	201	249	260	308	275
Other	69	68	68	62	78	128	102	114	223	269	241
Engin	2733	2770	2917	2950	3258	3234	3711	3727	4292	4375	4343

Chart 4. Federal applied research by science and engineering field: FY1985–95.

Field	Total		Federal	Non-Federal	Federal	Non-Federal
	Millions of $$$	Percent	Millions	of $$$	Percent	Percent
Total S&E	19911	100	11957	7954	60	40
Total Sci	16760	84	10098	6661	60	40
Total Environ	1317	6.6	870	447	66	34
Atmos Sci	211	1.1	160	51	76	24
Earth Sci	415	2.1	242	172	58	42
Ocean	460	2.3	331	128	72	28
Other	229	1.2	135	94	59	41
Total Eng	3151	15.8	1858	1293	59	41

Chart 5. Federal and nonfederal R&D expenditures at academic institutions, by field and sources of funds; 1993.

Total R&D	FY97 Estimate	FY 98 Budget	FY99 Projected	FY 2000 Projected	FY 2001 Projected	2002 Projected	% Change current $	FY97-02 Constant $
Defense	37461	36780	35870	34190	33672	35056	-6.4%	-17.7%
NASA	9315	9604	9537	9387	9293	9331	0.2%	-11.9%
Energy	6129	7250	6185	5967	5962	5886	-4.0%	-15.5%
- Defense	2775	3676	2543	2514	2583	2558	-7.9%	-19.0%
- NonDef	3353	3574	3642	3453	3377	3330	-0.7%	-12.7%
NSF	2424	2519	2530	2536	2543	2550	5.2%	-7.5%
Interior	581	608	608	609	609	610	5.0%	-7.6%
Transportation	650	684	684	684	684	684	5.2%	-7.4%
EPA	510	554	571	588	605	624	22.3%	7.6%

Chart 6. Analysis of Projected effects of President's FY 1998 Budget on Federal R&D (budget authority in millions of dollars).

targeted toward environmental protection funds spent. When compared to energy expenses, the amounts (except for Japan) are similar. However, the US far exceeds other countries in defense R&D funded projects. While the number is large, there are large sums (several billions of dollars) spent under defense programs that are targeted for environmental restoration of closed military bases throughout the US and other environmental R&D costs that are not readily apparent in the total defense funding numbers. Appendix B gives more details on US DOD funding areas for ESTs.

Chart 2 shows that the USA total for R&D in science and engineering was $28 billion in FY95 (last year when actual figures were available). That amount does not account for administration and operations of federal agencies which according to Science and Technology in Congress (May 1996, p. 3) amounted to $102.6 billion in the same FY95. The same journal estimated for the FY97 Budget that the request was about $300 million less or $102.3 billion.

Chart 3 specifies the amount of money in millions US$spent by the Federal Government for basic research by science and engineering fields for the period of 1985–1995. When data contained in Chart 3 is compared with those contained in Chart 4 for applied research in the same fields, it appears that basic non-defense research has garnered steady increasing funds over the above stated 10-year period. Thus, federal and nonfederal R&D expenditures at academic institutions by field and source of funds, as specified for 1993 (NSF, 1996, p. 172) in Chart 5, remain fairly consistent throughout the 1990s in large part since the research is primarily considered "basic" by the federal funding authorities (Congress, Clinton Administration, Departments and Agencies).

Finally, Chart 6 provides details on defense and non-defense budget proposals by the President projected to 2002. It may be noted that, in contrast to other federal funds for R&D, the NSF budget projections from 1996–2002, show only a small reduction (NSF, 1997) since, as in the case of academic institutions, its research is considered "basic".

In reviewing figures and data as contained in the Charts 1–6, the following general observation can be made: Federal funding of ESTs is difficult, is not impossible to isolate in terms of specific areas within the agencies and departments. We must assume, therefore, that life sciences, environmental sciences and certain portions of engineering are seen as part of publicly funded ESTs. However, Berg and Ferrier (1997) also note that "the development of new manufacturing technologies may be pertinent to the environmental, but be reported as manufacturing R&D" (1997, Chapter 3, p. 40) and hence not clearly seen as ESTs. Specifically referring to R&D for environmental technologies, Berg and Ferrier (1997) note that "Formal systems for reporting R&D sponsorship are incomplete and even for federally sponsored R&D, reported in ways that make the information hard to interpret" (1997, Chapter 3, pp. 39–40) The reason is that the actual publicly funded R&D work is embedded in the agencies and departments that does not allow any distinction between R&D funding and administrate costs. Hence, while program divisions can be identified, there are funds expended for R&D projects whose budgets also reflect administrative bureaucracy costs.

In the end, the most feasible approach seems to be to examine the overall budgets for those federal agencies and departments that fund ESTs. In Chart 6, the most recent funding patterns are reflected. Noticeably absent is the US DOC (NIST programs in ATP and TRP) since much of these funded are scheduled to be reduced in FY97 and it is too difficult to isolate the EST projects within each of the budgets. For FY98, the ATP was authorized around $200 million. TRP will receive about the same amount. Both programs are set to disappear within the next two fiscal year budgets, so that there will be no new funding at the turn of the century. Funding

ATP and TRP are considered obligations to on-going R&D projects.

Dr. Francis Narin recently published quantitative data that documents a connection between US publicly funded R&D and commercial interests as seen in patent citation data. In Narin et al. (1998, Fig. 21, see attachments) documents how industrial patent citations in chemistry and physics are directly linked to publicly funded R&D support from the top US federal agencies and departments. In other words, publicly funded R&D in science directly impacts economic growth. Narin, of course, assumes that patents are a significant business strategy or economic indicator and that quantitative patent citations are hard evidence and central to support that argument. To date, the methodology and resultant findings are the best empirical data available. Industry, scholars, and government are then to agree with the correlative linkage between patents and business or economic development.

Therefore, skepticism must be brought to bear on statements, such as the recent Competitiveness of the US Environmental Products and Services Industry from the US DOC (March 25, 1997 draft): "The vast majority of US environmental R&D in the past two decades, which amounts to over $100 billion, has been conducted with little direction from the market or input from the private sector." (Berg and Ferrier, 1997, Chapter 1, p. 5).

Clearly, the market is not the ipso facto sole purveyor of environmental demand, needs and concern for ESTs or public environmental policy for that matter. Industry should not be the determining factor in consideration of publicly funded ESTs. Industry "demand" for ESTs often is narrowly defined to establish vested corporate interests, market share, competition, and sales/marketing. Hence, governments must continue to play a strong role in the diffusion of publicly funded ESTs.

The UCDOC Report is correct, however, in stating that there will be a $180 billion environmental industry in the near future and that it will evolve from a pollution control and waste management service industry into a totally integrated resource management industry expanding beyond the "traditional resources of water, energy, timber, and land but include materials, property, people, and information." (Berg and Ferrier, 1997, Chapter 1, p. 4). Critical to the future of the environmental industry is continuance of publicly funded R&D for ESTs and how these results get diffused into practical applications in concert with industry is the appropriate strategy.

Jones et al. (1997) explore a new theoretical perspective of corporate governance by combining transactional cost exchange analysis from economics with network theory from sociology. This theoretical perspective argues that corporate governance and firm operations need to be seen as both a matter of economic or transaction cost driven and part of social or business networks among actors. "Network governance is increasingly important but poorly understood" (Jones et al., 1997, p. 937) In other words, the firm is governed by people who have economic goals (quantifiable in terms of stock prices, revenues and profits/losses) and social networks (e.g. exchange of information and knowledge as ßbusiness strategies and new technologies). See Williamson (1994, 1996), Granovetter (1992, 1994), Jones (1996) and Jones et al. (1997) for more details on theories from transaction cost exchange and social networks in business governance.

New technologies through research and development play a key role in network governance since the exchange of information or what Jones and others label "structural embeddness" whereby people exchange "knowledge" in a variety of informal circumstances. Saxenian (1994) noted the significance of this free flow of information exchange as part of the continued successful growth in Silicon Valley as opposed to the demise in the Route #128 high tech area surrounding Boston due to the restricted information flow. In other words, the people who create new technologies interacted frequently in one geographical region (for a variety of other reasons also, see Saxenian 1994; Jones et al., 1997 for details).

4. The case of remote communities

Most remote Alaskan communities pay economic penalties for electricity (ARECA, 1996), because they must import diesel as their primary fuel for electric power production, paying heavy transportation costs and potentially causing environmental damage with empty drums, leakage, and spills. Furthermore, the consumption of fossil fuels and the local negative environmental impact caused by communities befouling the region with leaking tanks and discarded drums must be considered when examining remote energy options. High fuel costs and environmental impacts occur not just in Alaska but also many locations worldwide where remote communities need power, regardless of climate.

Modern renewable resources and advanced technologies, coupled with state-of-the-art energy storage methods, compete favorably with conventional fossil fuel generation, when analytical comparisons are optimized to include life-cycle costs for the entire integrated energy system. This is true particularly where electric costs are high because of fuel transportation expense, there is a reasonable renewable resource available (e.g., wind, low-head hydro, solar, geothermal, etc.), and there is no inter-connection to a large-scale power grid. A modular approach to energy systems further allows the transition from a hybrid (for example, the combination of fossil fuel and renewable energy generation) to a totally renewable system as new technologies and applications become commercially available.

Resources such as wind and sunlight, however, are not continuously available in any region. The greatest reduction in fossil fuel consumption can be achieved, therefore, by using energy storage strategies and newly available technologies, capable of storing energy for periods of several days to more than a week. Effective long-term storage can, for example, be provided by using surplus power from renewable resources to electrolyze water, producing hydrogen, which can be later used to re-generate electricity in either fuel cells or with internal combustion engines. Alternatively, energy can also be stored in the form of reformulated, or recovered zinc pellets which are later used to generate electricity in a zinc-air fuel cell. In both cases, the technologies exist today and are now being commercialized (see Moore, 1997; The Economist, 1997).

Renewable energy combined with energy storage also has the potential to provide the very important benefit of increased system reliability, which has been recognized as one of the highest priorities in the design of remote power systems (Brown et al., 1996). Fuel cells, for example, have no moving parts, require almost no maintenance, and have long useful lives. Reliability can be enhanced by a distributed generation facility, combined with storage, and optimized through systems codes; potentially using the existing diesel generating system as a backup (Smith et al., 1997).

Public and private sector research has developed and demonstrated numerous renewable energy technologies (Clark, 1997). Widespread use of renewable energy technologies has been limited, however, by high costs (US Department of Commerce, 1997). Among other problems cited that prevent the commercialization of "environmentally sound technologies" have been (1) the market has been insufficient to stimulate mass production, (2) competition from inexpensive fossil fuels (the price of which commonly fails to include full environmental costs), and (3) the lack of integrated systems that take advantage of synergies possible between new technologies (The Economist, 1997). Nevertheless, a growing literature indicates that environmental and energy market demand is being created and supported through changes in governmental regulations. This leads to a stronger competitive advantage for private sector firms marketing 'alternative' technologies (Porter and van der Linde, 1995; UN, 1994, 1995; Clark, 1997; Clark and Paolucci, 1997).

5. Scope

This paper presents an analysis of remote power systems for an Alaskan community, demonstrating how a hybrid of technologies is far superior in optimizing energy efficiency, preventing environmental degradation, and reducing costs. The analysis shows significant potential advantages in terms of lower costs and reduced fuel consumption. Two computer codes provide the basis for our analysis. The first is a renewable grid analysis tool, and the second is an optimizer. These two codes combine to obtain optimum designs for any number of decision variables, as well as equality and inequality constraints.

This hypothetical remote village analysis treats optimization primarily as an energy cost problem, not as an environmentally driven problem. Thus no externalities (such as environmental regulations, legislative initiatives, and system reliability), nor potential linkages to water and waste disposal infrastructure are included in the analysis. Chapman (1996) estimated the substantial cost of environmental degradation due to emissions and spills that result from diesel engine operation at \$0.80 per liter of fuel (\$3/gal). If such 'hidden costs' and further integration with other community needs were taken into account, we expect the advanced technologies discussed herein would appear even more favorable.

Costs are very sensitive to a long list of parameters, both local and external to the village. This sensitivity makes cost comparisons difficult (Guichard, 1994). The results obtained in the analysis are expected to indicate trends that would exist in an actual village in which the conditions are not too different from those assumed here.

6. Methodology and scenarios: the remote community[3]

The coastal village used in the analysis is fictional, in that it has the demands of Deering (48 homes, population 150), and the solar insulation, wind and temperature data from Kotzebue. The parameters, data, and verification are based on profiles provided by the University of Alaska, Mechanical Engineering Department. Further data were provided directly from actual remote Alaskan communities. Wind speed data have been scaled to 8 m/s average wind speed, which is a realistic value for sites along coastal Alaska. Although we considered the possibility of including photovoltaic (PV) cells in the system, this evaluation indicated that wind was the preferred renewable resource in this sample case. Consequently, the optimized solutions presented below all show zero PV components. Other analyses could include PV for remote communities, especially those in sunny and tropical regions.

Space and water heating are major contributors to the total energy demand in Alaskan villages (Koniag, Inc., 1995). For this reason, our integrated approach

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[3] Data from earlier study by Isherwood et al. (2000).

considers the possibility of covering part of the heating load with waste heat from power generation equipment, or with surplus renewable energy obtained during periods of high wind speed, to reduce the fuel consumption for heating homes and public buildings.

Four modular energy systems are analyzed and compared in this paper. The systems are:

- *Diesel-only, base-case*: This is the system that currently exists in most Alaskan villages. Diesel gensets produce electricity, with heating provided by available waste heat first, then by diesel-burning furnaces (except that most real villages do not fully utilize available waste heat from gensets, partly because noise and safety factors place gensets far away from the greatest heating loads.). Our hypothetical village uses 250,000 l per year (250 kl/yr) of diesel for electrical generation and 135 kl/yr for heating.
- *Hybrid wind–diesel system*: This system includes wind turbines and diesel generators. Wind turbines generate electricity to satisfy the power demand (70 kW average, 118 kW 1 h peak). If there is surplus electricity after the power demand is satisfied, the surplus electricity provides heating for homes. As in the base-case system, diesel generators cover the electrical load and diesel-furnaces provide the heat when there is not enough wind to satisfy the electrical demand.
- *Wind–hydrogen storage–fuel cell–diesel*: This system includes wind turbines, an electrolyzer, vessels for low-pressure compressed hydrogen storage (4.1 MPa, 600 psi), an off-the-shelf phosphoric acid fuel cell (PAFC), and backup diesel generators. Proton exchange membrane (PEM) and solid oxide fuel cells (SOFCs) may soon be available with similar or even more suitable characteristics, but for simplicity, the current analysis included only the PAFCs for use with hydrogen. Wind turbines first satisfy the power demand. If there is surplus electricity after the power demand is satisfied, it can be used for either heating homes or for generating hydrogen for storage. When the wind turbines cannot satisfy the electrical demand, the fuel cell provides power to the system. If stored hydrogen becomes exhausted, the genset comes on line.
- Hydrogen storage has an economic advantage over lead-acid batteries for long-term storage, in that increased energy storage (measured in kilowatt-hours) is added by increasing only the hydrogen storage, at relatively low cost per kilowatt-hour. Low-pressure hydrogen storage is a safe, proven, and readily available technology. Reliable fuel cells can then utilize the hydrogen to generate electricity. Although the overall turnaround efficiency of electricity storage and retrieval from the system is only about 30%, heat from the fuel cells and electrolyzers can be used for space or process heating, substantially increasing the overall energy efficiency. Because fuel cells are practically noiseless, they can be placed close to facilities that can utilize their 'waste' heat.
- *Wind–zinc storage–zinc–air fuel cell–diesel*: This system is similar in strategy and components as the previous one, the only exception being that zinc pellets produced in an electrolytic process are used for energy storage, and a zinc–air fuel cell is used to generate electricity. Prototype zinc–air cells have demonstrated a turn-around electricity storage efficiency of about 60%, compared to 70% for lead-acid batteries (Cooper et al., 1995). As with hydrogen fuel cells, use of the waste heat from a zinc–air cell can bring the overall energy efficiency significantly higher. Zinc–air cells present none of the disposal problems of lead-acid batteries and have a considerable per-unit-energy weight advantage, which is important for shipping.

Particulate zinc–air fuel cells should soon (within 2 years) become commercially available and the total production costs should easily compete with lead-acid batteries on a per kW (power) basis. But as with hydrogen, the cost of incremental energy storage capacity (kWh) is quite low, making these cells particularly advantageous for long-term storage. Costs used in this study are based upon an industrial partner's estimate for commercialization of new technologies.

7. Results

The energy control strategy for the storage system is critical to the operation of the grid itself. Two of the possible options are:

1. Heating first: Surplus renewable electricity is used for resistive heating within the village. If there is surplus electricity after providing all the required heat, the electricity is used for generating either hydrogen or zinc for the storage.
2. Storage first: Surplus renewable electricity is stored as either hydrogen or zinc. If the storage system is full, surplus electricity is then used for heating the homes.

A preliminary analysis has shown that the heating first strategy has an advantage for the conditions analyzed in this paper. Therefore, heating first is the strategy selected for this analysis.

Table 3a shows the results of the example system optimization for minimum yearly cost, for a \$0.66/l (\$2.50/gal) fuel cost, and the zero interest rate, no cost escalation scenario. Table 3b shows results of the same optimization with the alternative economic assumptions; 8% interest, 3% maintenance cost escalation, but still no fuel cost escalation. The tables list the values of the five decision variables, as well as the fuel consumption and cost values.

The tables indicate none of the lowest cost systems have a photovoltaic component. Intrinsic solar irradiation is low at our model village, but the lack of PV here is most directly a consequence of today's still relatively high PV costs. However, PV costs have declined sharply in the past, and further declines are expected, perhaps sufficient for PV electricity to compete economically with other sources used in rural Alaskan communities within a few years.

The results in Table 3 indicate that maintenance costs dominate the economics for the base-case system. The importance of maintenance costs has been stressed in previous reports (e.g., AVEC, 1996; Harris et al., 1997). Most of the maintenance cost is associated with diesel genset operation. For this reason, optimum renewable systems tend to reduce diesel genset operation as much as possible. For example with the zinc–air fuel cell system, there is almost no need to operate the diesel genset, although the analysis considers that the diesel genset is kept as a part of the system for increased reliability (i.e., capital cost for the genset is included).

The wind–diesel system reduces diesel genset use to about a third, and total fuel consumption to less than half of the base-case values. Considering the moderate investment and the short time for payback required for these systems, installation of wind turbines constitute a good first step that can later be enhanced to include energy storage as additional capital is available for investment.

Fig. 1a and b show optimization results for the same two economic assumptions. The figures show total system cost and total diesel consumption for the four systems being considered. In addition to the fuel cost considered for Table 3 ($0.66/1; $2.50/gal), two more values are used: $0.40/1 ($1.50/gal), and $0.92/1 ($2.50/gal). The figures show that the yearly cost for the base-case system is very sensitive to fuel cost. For the systems with storage, fuel consumption is significantly reduced so that the yearly cost is less sensitive to fuel cost. The figure illustrates clearly the potential for cost and fuel consumption reduction obtainable by using renewable electricity generation in the village. Note the general similarity in results between the different economic cases. For brevity, the following figures present data only from the simple—no interest, no escalation—case, with confidence that general conclusions will not differ significantly over a broad spectrum of realistic economic assumptions.

Fig. 2 illustrates the results of a system optimization when only the electricity demand is considered (no heating load is satisfied). The cost and fuel savings for systems with storage appear even greater in when heating is neglected. We show this for comparison with other studies that do not integrate heating with power. Consideration of the total energy picture makes more sense for village planners. Optimum (lowest yearly cost) designs for the zinc–air fuel cell can reduce diesel fuel consumption to almost zero, so that the operating cost is independent of fuel cost (the time for payback is still a function of fuel cost). Wind–diesel systems can reduce fuel consumption to about 40% of the original value, and the cost to almost 50%.

Figs. 3 and 4 show the results of a parametric analysis for a system with hydrogen storage and a PAFC. Fig. 3 shows lines of constant total fuel consumption as a function of energy storage capacity and installed wind power. The numbers on the curves indicate the fraction of the fuel consumed in the base-case (384,000 l/year). Decision variables are set to the optimum values for the PAFC system from Table 3a. For low wind capacity ('low-penetration'), storage provides little benefit, since all of the electricity produced is immediately used to satisfy either electrical load or electrical-heating load, and the storage system remains empty. As the wind capacity increases ('high penetration'), the benefit of energy storage increases. A point in the figure indicates the optimum design from Table 3a.

Fig. 4 shows lines of constant fuel consumption for electricity generation only, as a function of energy storage capacity and installed wind power for the same system with hydrogen storage and a PAFC, with the optimum values for the decision variables from Table 3a. The numbers on the curves indicate the fraction of the fuel consumed in the base-case (250,000 l/year). As previously discussed, operation and maintenance of the diesel engines is expensive, and therefore the optimum design reduces considerably the fuel consumption for electricity generation.

Figs. 5 and 6 show results that are similar to those presented in Figs. 3 and 4, except that now the system being considered is the zinc–air fuel cell as energy storage. The decision variables take their optimum values from Table 3. Zinc–air fuel cells and storage are expected to be cheaper that PAFC and hydrogen storage, so that the optimum amount of storage, indicated by a point in the figure, is higher than for hydrogen. The higher efficiency of the zinc–air fuel cell results in very low fuel consumption for electricity generation. Total fuel consumption remains at about the same level as obtained for the PAFC system.

8. Analyses

Application of an analysis code and an optimizer to the problem of sizing a renewable electricity generation grid in a remote Alaskan village demonstrates significant potential for life-cycle cost savings. We compared a base-case system, which consists of (1) diesel gensets and diesel heaters, to three highly reliable systems that include renewable electricity generation: (2) a wind–diesel system, (3) a wind–diesel system with hydrogen storage and a phosphoric acid fuel cell (available 'off-the-shelf'), and (4) a wind–diesel system with zinc storage and a zinc–air fuel cell (expected to be available within 2 years). The results show that, for the conditions used for this analysis, fuel consumption and annualized life-cycle costs can be substantially reduced by using renewable electricity generation technologies as well as energy storage devices. Specific results from the analyses demonstrate that:

1. When wind turbines are added to diesel gensets ("wind–diesel" hybrid), the saving of diesel fuel can be more than 50% at a cost savings of over 30%. This is the most cost effective, quickest payback configuration for a remote village that has sufficient wind resource. Furthermore, wind turbines can be added incrementally, with additional maintenance and operational savings at every increment.
2. When energy storage devices are added (e.g., hydrogen or zinc–air), diesel fuel consumption and costs can be reduced substantially more. Optimized energy storage allows diesel gensets to be eliminated. However, about one quarter of the original diesel consumption is still required to satisfy heating demands.
3. Costs using optimized hydrogen storage can be 10–20% lower than for wind–diesel alone, while displacing about an additional 20% of the original diesel fuel consumption.
4. Using estimated costs for zinc–air technology for energy storage, as much as 75% of the current diesel fuel can be displaced with 30–40% cost savings over wind–diesel without storage. This result provides a strong incentive to further speed the commercialization of this technology.
5. There are a number of externalities that have not been factored in at this point, but could be in future analyses. For Alaska, we suggest the externalities include: environmental impact and regulations, political legislation and funding (direct investment, incentives, and taxes), and specific community-based variables such as employment opportunities and need for reliable service. The advantages of not needing to send hard currency out of the village for expendable fuel and reducing environmental threats provide additional incentives not included in this analysis.
6. Further benefit can be gained by combining any energy system upgrades with a review of energy efficiency and demand-side management options. Education and training programs need to be an integral part of the installation, maintenance, and operation of such new energy systems. Expertise gained in this area would be a very viable and significant commodity for international commercial exploitation through university and vocational training programs.
7. Finally, there are economic and business opportunities for Alaska in advancing such modular energy systems. For example, seven other countries share the remote Arctic conditions, with similar energy base-case scenarios and needs. Also new industries for energy modular systems as well as advanced energy storage technologies could be developed within the State.

It is expected that refinements possible during the analysis of a real village could potentially make the economics more or less favorable. In general, we believe the benefits shown possible in these analyses should be realizable at numerous sites throughout Alaska.

The systems described in this paper should be robust enough for application in real communities and could be modular enough for additions and substitutions of new technologies as they become available. In short, a key concept is the creation of new energy systems that are economically viable and sufficiently flexible for implementation of new technological advances.

A recent issue of The Economist, featured a story in its Science and Technology section, "At last, the fuel cell" which stated in part: scientists "seem to have created something that may revolutionize two industries—power generation and motor cars" which "makes fuel cells a double friend to the environment: if put in vehicles, they would not pollute the city streets; if put in power stations (or vehicles, for that matter) they could not add to any global warming that might be going on." (The Economist, 1997). The time has come for advanced energy technologies to preserve the environment while providing for new energy resources that reverse global warming and climate change.

9. Conclusions

Distributed generation can be achieved in communities through a combination of efforts that optimize or combine both advanced technologies (such as wind and fuel cells) alone with a variety of environmentally sound technologies. Such new environmental-energy technologies such as fuel cells and flywheels (e.g., see Clark 1996; Clark and Paolucci, 1997) developed in universities and American national laboratories can provide technological solutions to environmental and energy issues, in part legislated by governmental regulations, while creating new business opportunities and economic systems. Distributed energy systems must be systemic in that government and the public sector must play an active planning role in the integration of advanced technologies to reduce cost and increase efficiencies.

Intense and constant interaction must guided by the public sector to take place between the market pull of the private sector—such as manufactures, energy, and power companies—and the government supported technology push providers—such as research institutions like universities and national laboratories—in order to commercialize new technologies. Such close collaboration supersedes industrial competitive issues and problems in an interactive non-linear economic system (Clark and Fast, 2004). In other words, the typical economic analysis that presents demand versus supply fails, because the business process is really one that is a constant interactive process.

The role of government has shifted from pure regulatory concerns to financial support and internationalization (through bank guarantees, patent protection, trade agreements and other means). Such new "civic markets" (Clark and Lund, 2001) provide the platform for distributed generation systems. Clark and Bradsaw (2004) portray these systems as being "agile" in that they must be regionally and locally based. The emergence of international strategic alliances between partners in the environmental industry and the federal government is the most viable approach for transferring ESTs into other countries. Along with such a strategic must be concern over issues of intellectual property, equity and debt financing, profits and losses, and management of companies. In short, government can take the risks in R&D that industry is loath to do.

Capital and finance remain the key to transferring technologies from the research culture to the international business culture. Again government plays a key role: it can provide the contacts and capital to move technologies into the marketplace. Two things need to change (at least more rapidly): one is that government can take an "equity" (see below on university and laboratory policies) in companies that it supports. Such a role for government would also necessitate it taking an on-going role in the oversight and management of the company as well (Clark and Jensen, 1994, 2001).

The other change for government concerns its need to coordinate and even collaborate with industry on public policy with technology research and development. ESTs is an excellent example about how this might occur. Regulations for zero emission vehicles in California, federal clean water acts and other others have been an impetus and catalyst for new inventions to solve environmental problems. Research funds need to be made available to fund multiple solutions.

Appendix A. Data summary from Isherwood et al. (2000)

A.1. Optimization code analyses

A remote village system analysis code has been developed specifically for this project and then integrated to an optimizer. The purpose of this work is not to duplicate the extensive capabilities of an existing hybrid systems code (HYBRID2, Baring-Gould, 1996; Manwell et al., 1996), which can also be linked to an optimizer (Flowers, 1997). Instead, the purpose is to have an energy system code that can easily incorporate new advanced technologies (such as energy storage devices), waste heat recovery systems, and operating strategies, for optimization into modular systems suitable for remote villages.

The US Magnetic Fusion Program at Lawrence Livermore National Laboratory originally developed SUPERCODE in the early 1990s for optimizing tokamak reactors and experimental designs (Galambos et al., 1995). SUPERCODE is a shell that incorporates process models and non-linear equations with uncertainty, which has subsequently been used to optimize inertial fusion devices, rail-guns, and hybrid-electric vehicles (Haney et al., 1995), in addition to the present application.

A powerful programmable shell that takes input using a variant of the C++ language controls SUPERCODE, and has more recently been converted to Mathematica (Perkins et al., 1997). Input can be from a terminal or from files, allowing interactive or batch operation. The user can define real, integer, complex, array, and string variables. In addition, the language supports control statements, loops and functions. Finally, the SUPERCODE shell can exploit the multiprocessing capabilities of UNIX to run external programs, such as this village simulation code, to compute constraint and figure-of-merit values. It is even possible to use the parallel virtual machine system (Beguelin et al., 1991) to simultaneously run multiple copies of the externalprogram in parallel on a number of workstations thereby dramatically reducing execution time.

This programmable shell offers tremendous flexibility for the user to specify an optimization problem. Once the optimization is completed, the user can interrogate the shell for variable and figure-of-merit values. Also, variables can be fixed, or new constraints applied to investigate "what-if" scenarios. Finally, loops can be written to perform parameter scans.

The community optimization code includes:

1. Electricity generation components: These are defined by vectors that specify electricity output for every value of energy input (wind speed, solar irradiation, or fuel consumption for a diesel genset or fuel cell).
2. Loads: Electrical loads are taken from Deering, Alaska. Average demand is 70 kW, and the 1-h peak is 118 kW. Average heating load is assumed equal to 150 kW for the whole village. We assumed that 85% of the heating load goes for space heating and 15% for water heating. The space heating load is distributed along the year based on the temperature

data for the village. The water heating load is distributed uniformly throughout the year.

3. Energy storage components: These vectors specify the efficiency as a function of power input.
4. Waste heat recovery: This component specifies the fraction of the total waste heat that can be used for heating, and the maximum percentage of the village that can be heated with waste heat.
5. Energy storage strategy: Surplus electricity can be either stored by electrolyzing water to make hydrogen or recovering zinc from the zinc–air fuel cell sludge, or used for heating the homes. The systems analysis code offers the possibility of analyzing both of these options for any particular scenario.
6. Economic analysis: The code calculates annualized operating costs and years for return of investment as a function of all the system cost parameters, fuel consumption and maintenance of the system, which are in turn functions of equipment performance and use. Options include separate rates for the cost of capital (interest rate), fuel cost escalation, and maintenance cost escalation.

A.2. Optimization of remote community energy systems and advanced technologies

Table 1 list the parameters used in the test village analysis. The analysis assumes that 40% of the waste heat generated from the diesel engine can be used for heating. This value corresponds closely to the amount of waste heat transferred to the cooling water (Malosh et al., 1985). The rest of the waste heat is lost through the exhaust pipe, and it is not recovered in current power plants. For fuel cells, we assume that most of the waste heat (60%) is transferred to the cooling water, making it available for heating. We also assumed that in the diesel-only base-case a maximum of 30% of the village can be heated with waste heat. This is because diesel engines are likely to be located at a central power plant, so that waste heat can only be economically used in a few buildings. Fuel cells can be distributed through the village. If desired, each home could potentially have its own fuel cell. This affords a significantly higher potential for heating with waste heat recovery (50%).

Diesel engines present operating difficulties if operated at very low load. For that reason, a minimum operating power (40% of full load, Malosh et al., 1985) is defined.

We present here two separate sets of economic assumptions to illustrate their effect. First we assumed no escalation of fuel or maintenance costs and used a 0% interest rate on capital, due to State or Federal subsidizes or other investment incentives. Published scenarios project fuel cost escalation to approximate or exceed the borrowing rate, making this approach a plausible first assumption. Furthermore, the state of Alaska currently subsidizes the electricity for the remote villages to a level of \$0.27/kWh (Jensen, 1997), so this case assumes that the State might be willing to provide low- or no-interest loans in order to reduce the future amount of the subsidies. The results are also presented

Table 1
Parameters for remote village electric grid

Distance from wind turbines to village, km	10
Average electric demand for village, kW	70
1-h peak demand for village, kW	118
Average wind speed, m/s	8
1-h peak wind speed, m/s	35
Average heating demand, kW	150
1-h peak heating demand, kW	365
Efficiency of diesel-fueled heater, %	80
Fraction of waste heat that can be used for heating, fuel cells, %	60
Fraction of heating load that can be met with waste heat, fuel cells, %	50
Fraction of waste heat that can be used for heating, diesel genset, %	40
Fraction of heating load that can be met with waste heat, base-case, %	30
Number of diesel gensets	3
Maximum diesel genset power, kW	60
Minimum diesel genset power, kW	24
Wind turbine maximum power output, kW	20
Maximum solar irradiation, kW/m^2	0.82
Fuel energy density, kWh/liter (kWh/gal)	9.51 (36)
Fuel cost, \$/liter (\$/gal)	0.40–0.92 (1.50–3.50)
Interest rate, %	0.0 and 8.0
Maintenance cost escalation, %	0.0 and 3.0
Fuel cost escalation, %	0.0 and 0.0

Table 2
Parameters for cost analysis of grid

Component	Life (yr)	Cost	Maintenance, \$/kWh
Transmission lines	20	\$10000/km	0.001
Compressed hydrogen storage	20	\$10/kWh	0.001
Electrolyzer	20[a]	\$1000/kW	0.001
diesel heater	10	\$100/kW	0.001
Electrical resistive heaters	20	\$20/kW	0.001
Engine-generator	4[a]	\$200/kW[a]	0.12[c]
Wind turbine	20	\$2400/Kw (installed)	0.03
PAFC fuel cell	20[a]	\$1500/kW[b]	0.01
Photovoltaic cells	20[a]	\$770/m^2 or \$5000/k\W (peak)	0.0[a]
Zinc storage	20	\$4/kWh	0.001
Zinc-air fuel cell	20	\$150/kW	0.01
Zinc recovery unit	20	\$150/kW	0.001

[a] From Guichard (1994).

[b] From Guichard (1994). Projection to 1998.

[c] From Malosh et al. (1985).

in terms of simple payback, which is independent on the interest rate.

For comparison, we also show results based on the fairly conservative economic assumptions that (1) diesel fuel costs do not escalate (based on recent history rather than escalating predictions such as those of the Energy Information Administration, 1997), (2) maintenance costs escalate at a 3% general rate of inflation, and (3) money for capital improvements can be borrowed at an 8% interest rate, As will be seen, these economic assumptions do not significantly alter the magnitude of benefit derived from the optimized power system scenarios described above.

Table 2 gives cost parameters for the main components in the power grid. Capital costs include transportation of equipment to the village and power system installation. Maintenance costs are very important since they can make or brake the economics of an installation (Energy Mines and Resources Canada, 1988; UN, 1994, 1997). Renewable modular energy systems are expected to have significantly lower maintenance costs than diesel systems. The individual components of wind-turbines, electrolyzers, and fuel cells have a good history from which to estimate maintenance costs (see, for instance, Guichard, 1994). Zinc–air technology is new, but the simple principles and similarity to hydrogen fuel cell technology provide a basis for assuming similar low maintenance costs.

Five parameters are used as decision variables:

1. Total wind turbine power capacity, in kW.
2. Total PV energy capacity, in kW.

Table 3

	Base-case	Wind–diesel	Hydrogen PAFC	Zinc–air
(a) System parameters for optimum designs presented in Fig. 1a, for a fuel cost of \$0.66/1 (\$2.50/gal), zero interest and no cost escalation				
Optimum system parameters:				
Wind power, kW	0.0	403	580	451
Energy storage, MWh	0.0	0.0	35.7	82.2
Electrolyzer power, kW	0.0	0.0	358	287
Fuel cell power, kW	0.0	0.0	96.8	122
Photovoltaic power, kW	0.0	0.0	0.0	0.0
Annual diesel fuel consumption, kl (kgal):				
For electricity generation	250(66.0)	85.6(22.6)	11.1(2.94)	0.0(0.0)
For heating	135(35.6)	78.1(20.6)	78.9(20.8)	95.9(25.3)
Total	384(101)	164(43.3)	90.0(23.8)	95.9(25.3)
System costs:				
Capital, k\$/yr	13.4	66.5	130	91.4
Maintenance, k\$/yr	286	164	77.5	49.2
Fuel, k\$/yr	253	108	59.5	63.3
Total, k\$/yr	553	338	267	204
Years for payback	—	4.0	5.84	3.68
(b) System parameters for optimum designs presented in Fig. 1b, for a fuel cost of \$0.66/1 (\$2.50/gal), 8% interest, 3% maintenance cost escalation, and no fuel cost escalation.				
Optimum system parameters:				
Wind power, kW	0.0	351	538	446
Energy storage, MWh	0.0	0.0	22.3	47.6
Electrolyzer power, kW	0.0	0.0	294	298
Fuel cell power, kW	0.0	0.0	75.6	153
Photovoltaic power, kW	0.0	0.0	0.0	0.0
Annual diesel fuel consumption, kl (kgal):				
For electricity generation	250(66.0)	90.6(24.0)	24.0(6.38)	6.55(1.73)
For heating	135(35.6)	95.9(25.4)	82.5(25.4)	94.5(25.0)
Total	384(101)	187(49.4)	106(28.2)	101(26.8)
System costs:				
Capital, k\$/yr	19.0	115	225	165
Maintenance, k\$/yr	386	224	123	78.0
Fuel, k\$/yr	274	133	76.1	72.3
Total, k\$/yr	679	472	424	315
Years for payback	—	3.75	5.34	3.44

3. Energy storage capacity, in kWh.
4. Maximum possible power into storage (maximum electrolyzer/zinc recovery unit power).
5. Maximum possible power out of storage (maximum fuel cell power).

The specific figure-of-merit used for this optimization exercise is the yearly cost of the system. This includes capital, maintenance and fuel costs. The cost of fuel is assumed to be in the range of \$0.40/l (\$1.50 per gallon) to \$0.92/liter (\$3.50 per gallon).

Appendix B

Parameters for (1) remote village electric grid (Table 1); (2) parameters for cost analysis of grid (Table 2); (3) system parameters for optimum designs (Table 3).

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