Electrification of Energy

April 23, 2008
Cambridge, Massachusetts

WORKSHOP REPORT

Juha Kiviluoma and
Gustavo Collantes

Report on a workshop organized by the Energy Technology Innovation Policy research group of the Belfer Center for Science and International Affairs at Harvard University's John F. Kennedy School of Government.

The workshop was held at the Harvard Kennedy School on April 23, 2008.

1. Introduction

Use of electricity has been increasing faster than the use of energy for a long time. This trend could accelerate if the competitiveness of electricity in transport and heating continues to improve. Currently electricity accounts for a minor share of these major forms of energy end-use, but the potential for increased use of advanced vehicles with motive power and heat pumps could change the picture. Opportunities for electrification arise as fossil fuels for transport and heating become more expensive and concerns about the emission of greenhouse gases grow. There are huge alternative low-carbon resources — solar, wind and possibly geothermal and nuclear — from which electricity can be produced. Increased electrification of transport and heating would have profound implications for energy policy and the power sector.

On April 23, 2008, the Energy Technology Innovation Policy (ETIP) research group convened a workshop on *The Electrification of Energy*. This workshop brought together a small number of selected experts to discuss the opportunities for and challenges of the electrification of energy. The list of participants included representatives of the automobile industry, electric public utilities, government, non-governmental organizations, and academia (a list of participants is included at the end of this report). In this document, we summarize the key points presented during the various sessions.

2. Electrification of Transport

The first session of the workshop focused on the transport sector. The discussant started by proposing a definition of electrification of transportation as *the process by which electricity provides an increasing share of the automobile motive power*. This process starts with hybrid electric vehicles today on the road, and may continue with plug-in hybrids, fuel-cell vehicles, and battery electric vehicles. Some of the challenges related to **innovation** in new vehicle powertrain were identified, including uncertainty in innovation-drivers such as oil prices, and the value proposition that new vehicles may offer to consumers. Projections of future oil prices have been repeatedly off the mark, and they are usually presented as point estimates instead of ranges. This has implications for energy policy, particularly when radical technology innovations are involved. Energy policy and business strategies may look very different depending on whether the "best" estimate for oil prices or the high-price scenario are considered.

Understanding the **value proposition** of new vehicle technologies is essential in order to achieve the desired technology adoption. This is a key lesson from previous experiences with alternative fuels. New technologies need to be competitive vis-à-vis the standard gasoline internal combustion engine, and policies need to level the playing field by internalizing externalities, for example.

Following up on these introductory comments, it was suggested that we should be looking as well at the electrification potential of public transportation systems.

From a consumer standpoint, **driving range** and **recharging time** are key factors. For example, plug-in hybrids may offer typically 20 miles of all-electric range, extended-range electric vehicles may offer 40 miles of all electric range, and hydrogen fuel-cell vehicles may offer 200 to 300 miles. We are probably two technology generations away from a commercial fuel cell vehicle (each technology generation being three to four years.)

One way to understand plug-in hybrids is simply as a device for replacing a gallon of fuel every morning with the equivalent energy obtained from the grid. Another participant suggested that batteries could be not only recharged, but also rented, changed at a station and recharged at leisure. Responses to this suggestion included: a) The battery inventories that this approach would require are prohibitive; and b) Some PHEV designs approach batteries as an integral part of the vehicle structure, playing a role in the vehicle crashworthiness; under this approach, the concept of battery swapping becomes more complicated.

The value proposition of PHEV includes: a) Opportunity for consumers to wean themselves from the need to refuel at gas stations; b) The price of electricity is more stable than that of gasoline; c) Vehicles can be charged at night, when electricity demand and prices are lower. In the way of developing a mass market for PHEVs, it is crucial to figure out what the right **business model**/value proposition is. It was suggested that thinking in terms of fuel savings alone will not generate significant market interest. Another participant suggested that if fuel savings is the only driver, then HEVs can be more cost effective than PHEVs. However, many other factors should be incorporated, such as the potentially higher reduction in carbon emissions from PHEVs.

Setting the right price for externalities such as climate change and energy security is crucial if we want to start developing markets for cleaner vehicles. There are, however, questions regarding how consumers make decisions, what their implicit discount rates are, and how they would respond to a "right pricing" of externalities.

Some participants emphasized that the market for PHEV does not yet exist, or it is only a niche market at best. It was pointed out that the batteries needed for a commercial PHEV have not yet been developed fully. The main challenges identified were cost, power density, energy density, safety, durability, and weight. No precise estimates were given as to when automakers could be in a position to market these vehicles, but one participant ventured to say that significant sales may not happen before the 2020-2030 timeframe.

The importance of **recharging infrastructure** for consumer acceptance was highlighted. If a consumer is to pay a premium for a plug-in hybrid, she will need to have access to recharging infrastructure—at least at home, but ideally widespread. The availability of recharging infrastructure then will be a determining factor of the market potential of PHEV. Another participant agreed and said that consumers are spoiled, as they are accustomed to certain comfort standards for their vehicles and are unwilling to compromise on fuel availability, performance, etc.

A participant stressed the importance of figuring out a way to get vehicles on the road in large volumes. Another participant agreed, saying that auto companies are experts in mass marketing, but they struggle with the notion of niche markets.

It was suggested that there is a lot that policy can do to help develop markets for new vehicle technologies. A participant pointed to experiences in other countries, such as Sweden, where free parking and lower taxes are offered to consumers who buy low-emission vehicles. Another participant pointed to New Zealand's experience with compressed natural gas vehicles, indicating that government incentives were very important to motivating consumer adoption of these vehicles.

Follow-up research questions:

- What is the value proposition of PHEV to consumers and industry?
- What is the value added to PHEV by power ancillary services?
- Will there be a need to build an infrastructure for charging the vehicles, and if so, at what point?
- Does current legislation provide appropriate incentives to develop electrification technologies?
- What is the societal benefit of PHEV in terms of reducing carbon emissions and enhancing energy security?
- What is the time-scale of potential contributions of different approaches to the electrification of transport, while accounting for expected pace of technological developments and turnover of deployed technologies? What technical, economic and socio-political factors and uncertainties are most important in affecting the answers?
- What are the principal implications for electricity generation, transmission, and distribution arising from the various approaches to the electrification of the transport sector?

3. Electrification of heat production

Electrification of heat production could offer a similar magnitude of CO_2 emission reductions as electrification of transport, if low carbon electricity is used. Contrasted with plug-in electric vehicles, electric heat production is already commercial in some parts of the world, especially in Europe and East Asia. Participants suggested that the largest barrier to broader adoption of electric heat technology is the relatively **high upfront cost** of heat pumps, and this challenge might be exacerbated because home builders, who have incentives to cut their costs, will avoid more expensive heating equipment, even if such equipment would have a relatively fast payback period. Some countries have imposed building standards mandating high-efficiency heating systems; California, too, has such building codes. In the United States, however, even homeowners who could theoretically see the long-term financial benefits of installing electric heat-producing equipment might choose not to because of the "under-pricing" of heat. Some countries have "energy certificates" for homes, which help inform potential homeowners about the estimated costs of space heating and/or cooling, which have proven successful. In this vein, construction of energy efficient houses was seen in some places as a cultural issue starting from the architectural design phase. Lastly, some participants recognized that there are also institutional and regulatory challenges than hinder deeper penetration of electric heat production.

Current standards for heat pump equipment in the United States were seen as a pressing problem. Current standards rate heat pumps according to *cooling efficiencies*. This is

problematic because heat pumps optimized for cooling will perform poorly in cooler climatic regions, where they will be mostly producing heat. Some felt there is an urgent need to upgrade the standards to take different climatic regions into account.

Lack of information was seen as a problem at multiple levels. One noted that many individuals underestimate the extent to which heating and cooling dominate household energy demand. Furthermore, both commercial and residential users were seen to be poorly informed about their options as they relate to heating, and the relative merits of available options. Better real-time information has the potential to change consumer behavior as demonstrated by some gasoline-electric hybrid owners keeping close watch on their real-time gasoline consumption. There was concern that without access to real-time information, consumers' sensitivity to price signals is limited; participants suggested that this is problematic because a consumer's response to price signals is one of the most important ways that the market can induce behavioral change. Access to real-time information on household energy consumption, however, may be driven in part by the electrification of passenger vehicles, which could inspire use of integrated energy information/control devices for households. Such devices would also serve to maintain the integrity of the heat pumps, since diagnostic information could minimize the amount of efficiency loss from dirty or poorly-functioning pumps.

The **performance of current heat pumps** is quite far from theoretical Carnot efficiency, especially when compared what has been achieved in power plants. Improvements are being made and COP is already over 5 in new commercial air source heat pumps. However, air source heat pumps are much less efficient in cold weather, although technical solutions are improving the situation somewhat. Ground source heat pumps, on the other hand, don't suffer the same efficiency losses during cold weather, and despite their higher upfront costs, they are more competitive in colder climates.

Technological research on electric heat production equipment has mainly been happening outside of the United States. In Japan, utilities play a key role in technological innovation, and some noted that perhaps it is time for wide-scale pilot programs in the United States, some examples of which are already found in the U.S. Pacific Northwest. It was also suggested that utilities could play a role in supporting the development of a labor force with skills that are specific to heat pump technology; this will be important for scaling up a large number of small residential-scale installations.

Technological opportunities to improve the efficiency of heat pumps are not yet exhausted. Despite the potential increase in efficiencies, current heat pump technology is already close to cost-competitive with more traditional heat production methods in many applications. Given the breadth of applications, however, it is difficult to make a blanket statement regarding the competitiveness of heat pumps versus conventional technologies. There is a clear need to chart the market potential in much greater detail taking into account different heat and steam grades as well as climatic conditions and opportunities for retrofits.

There were concerns expressed about how heat pumps might affect **peak loads**. In regions where power demand peaks in the winter, heat pumps without power storage will increase peak power demand, unless they replace direct electric heating. In regions where power demand peaks in the summer, high efficiency air conditioning units that replace older

units should help to reduce peak loads, especially if they employ ice storage technologies. For example, highly efficient split A/C units that remove hot air from one location and bring cold air from another are very rare in the United States, but could go a long way to reduce summer peak energy demand. Efficient two-stage or variable speed compressors could further help to increase peak efficiencies. Ice storage technologies have higher upfront cost than conventional A/C units, and there was concern that they might be operating if nighttime temperatures are high and the unit is undersized. Possible learning opportunities were seen in vehicle A/C units, and one key area for further development was seen to be in power electronics.

On the subject of **industrial heat pump** applications, it was shown that energy demand for space and water heating applications are very high for many industries, and that heat pumps could reduce the energy demand for heating significantly. Some noted, however, that heat pumps cannot provide adequate steam temperatures or necessary temperature lifts for some industrial applications. Others posited that industries are very cost-sensitive and are capable of using sophisticated tools to analyze their energy requirements, and this could bode well for the growth of industrial-scale heat pump utilization. For example, pinch-analysis could help industries see where heat pumps could benefit the overall system. It was also noted that standards for industrial heat pumps are an important enabling tool.

In industrial applications, **combined heat and power** (CHP) production can be competitive with electric heat production. Concern was raised about how policies should be formulated so that regulators don't choose a winner between CHP and electric heat. It was noted that if the GHG reduction opportunities for electric heat were made explicit in any related legislation, this would be a useful policy driver for incentivizing electric heat. Further, it was noted that electric heat pumps could levelized heating costs, and the subsequent predictability of energy-related expenses would be important for the industrial sector.

Follow-up research questions:

- How would storing energy for heating and/or cooling affect the efficiencies of heat pumps and the power system? How would the economics of integrating intermittent power sources change when there is more flexibility in the power system?
- What will happen to power system CO_2 emissions with increasing use of heat pumps and heat storage technologies? Shifting peaks will not necessarily reduce CO_2 emissions, and doing so in any case yields different outcomes in the short term (marginal plant) and in the long term (new load profile and new power production investments). A further complication is that long-term emissions can be strongly affected by policy.
- What role might information technology play as a cross-cutting area between plug-in electric vehicles, household comfort and the power system?
- What kinds of business models would address the high upfront costs of electric heating systems?

- What is the potential rate of penetration of heat pumps in the currently fuel-served heat markets in the industry and in the residential and commercial buildings? What technical, economic and sociopolitical factors and uncertainties are most relevant?

4. Power systems and power markets

The session began with a challenging question: how should we plan for upgrades to the power system, if we take into account the possibility of increased electrification?

It was suggested that lot of the issues would be resolved if the **prices** were right, both in real-time and also including externalities of energy production. For instance, it was noted that subsidies create a gap between the value of electricity and the prices that customers are willing to pay for it. There were concerns about how consumers would react to real-time pricing and what kinds of arrangements should be made that would both provide for better management of the risks and keep the incentives for efficiency in place. One response was that consumers might prefer a flat rate for their energy consumption, much the same way as cell phone users pay a flat monthly rate for their cellular communication services. However, if such a scheme was implemented, it was noted that people should at least be able to opt-out, as seen in the system employed by PJM. A hybrid system was also proposed where the flat rate would have rebates based on real-time pricing. Consumer participation in the electricity market was overall seen as a good tool to reduce supply-side control on the market.

A warning was expressed that **infrastructure issues** for increased electrification are not trivial. For example, charging stations that can accommodate higher voltages than what is common today would be needed, and such stations would need to be installed in garages and other places where people park their vehicles. However, it was noted that household high voltage systems could pose a potential hazard to public safety, and that system design should take this into account. There was some disagreement regarding the convenience of plugging in nightly versus visiting a gas station occasionally. It was noted that some prospective plug-in electric vehicle owners might not be able or willing to plug-in every night, or they might be afraid of getting stranded with an empty battery. However, if a large number of plug-in electric vehicles were in the vehicle fleet, then an infrastructure for routine and emergency recharging would be likely to emerge.

How the power markets and power system would change if **electricity** was made into a **commodity** with large enough storage capacity was another question posed. As reference, it was noted that coal, oil and natural gas are stored for 20-50 days, and that plug-in electric vehicles would not provide large amounts of stored electricity. On the other hand, plug-in vehicles could offer a large amount of power capacity and as such could be very useful in providing services that require capacity, such as primary reserves. It was mentioned that heat pumps with heat storage technologies could offer large amounts of energy storage for the power system, although they would not be capable of discharging to the power grid, with the exception of Stirling heat pumps. It was pointed out that there could be competing uses for the electricity storage in the vehicle batteries: grid support, local back-up, and of course, vehicle power.

Ancillary services with plug-in electric vehicles were discussed to some extent. It was noted that V2G is not necessary for all types of ancillary services, since vehicles that are charging can pause if necessary and therefore act as a demand response. It was unclear during the discussion how large a share of ancillary services plug-in electric vehicles could provide, but it was established that there are differences between various services. Related to this, one participant noted that it would be easier to provide capacity-related services than energy-related services, since the amount of stored electricity would be quite small. Some ancillary services could be entirely provided by plug-in electric vehicles, which means that there are decreasing marginal benefits from plug-in vehicles for the power system. However, if there is a higher share of variable power production from wind and solar, then the need for some services, especially load-following services, would increase. The first plug-in vehicles participating in the ancillary service markets might create considerable benefits per vehicle and this could be important in getting the first electric vehicles in the road, but the benefits have to trickle down to the end-users, unless some entity pays for part of the upfront vehicle cost in exchange for capability to profit from the power system benefits.

In terms of building a V2G infrastructure, the structure of **utilities** has a lot of heterogeneity and there was concern about how **car manufacturers** can both understand and cope with the different practices. It was pointed out that there are only ten system operators in the United States, so operating at this level should ease matters.

After some participants expressed concern about how power markets could cope with **millions of individual demand nodes**, it was noted that statistical aggregation should work well and that current models and computers actually are capable of coping with very large and complex systems.

The last major question taken up in this section was whether or not the energy system should be designed based on the **desired outcome**. It was noted that there is a lot of inherent uncertainty in attempts to determine the desired outcome and that this might not be feasible. One major source of uncertainty is innovation. How to take into account the possible long-run benefits from things we don't know yet? However, innovation in the energy domain was seen to be important and it was noted that getting the price right can promote innovation, although societal R&D investments were also seen as pivotal due to the long and uncertain R&D payback periods.

Follow-up research questions:

- How should electric utilities and car manufacturers interact? What would be the ideal interface between the two, and what kinds of business models would be feasible?
- What is the importance of power peaks? Is the largest problem in transmission, cost of peaking units, or in the uncertainty of peak capacity level?
- How would an economy-wide cap-and-trade system affect plug-in hybrid economics?
- How do the impacts and benefits change when the electricity storage capacity in the power system grows over time? It was noted on this last point that partial answers to this question might be found by looking at systems containing a high share of reservoir hydro power. How does one quantify and marketize the actual storage

benefit of the batteries on vehicles, which might be moving or parked, connected or unconnected, charging or discharging?

- Which smart grid benefits are worth their costs and what are the business models to make them happen?
- What are the political and regulatory hurdles to getting the benefits that technology and economics indicate are there?

5. Electrification in Global Energy Models and Scenarios

The fourth session tried to establish a link between models and scenarios of global energy futures and the electrification themes of the workshop. Clearly, if electrification proceeds at a pace laid out by existing energy models, then the mix of **primary energy sources** will be very different than what we have today. This could have important ramifications for climate policy and would be an important driver for the possible electrification of transport and/or heat production. One sample scenario laid out at the workshop showed a near doubling of electricity share of final energy by the end of the century – to 35%. This is in line with historical trends of increased use of electricity. However, the amount of electrification discussed during the workshop would go well beyond this. Therefore, it was fair to ask how useful current generation global energy models are for illuminating the degree of penetration of the particular types of electrification discussed in the workshop. Models inform the policy making process, especially through the work of the IPCC. It was questioned how flexible the demand for electricity is to changing circumstances; some noted that the mix of energy sources changes more readily in the global models.

Electrification would increase electricity consumption. GHG emissions would depend on the sources of electricity and there was discussion about different low carbon electricity sources. However, required energy services can be provided without electrification and therefore **emissions and associated costs** should be the main criteria for deciding on the right pathway. Electrification is not an end by itself. However, it was noted that electricity could be an efficient way to use primary energy, regardless of its source, in most applications. Another factor that global models should incorporate is renewable resources and the variability associated with some renewable options. Hydrocarbon resources are also subject to uncertainty, and model results are affected by these estimates. Regardless, the scale on which any future low carbon energy source has to operate is very large compared to the status quo, and all of them have their own challenges in scaling up. For nuclear energy, the challenges are waste disposal, uranium availability and proliferation issues, though they depend on the chosen nuclear pathway. Carbon capture and storage technologies have yet to be demonstrated on large scale and will have a considerable effect on the cost of hydrocarbon-based electricity. Renewable sources are heterogeneous but at least one of the following challenges applies to each of them: cost, intermittency, resource or land-use constraints.

Follow-up research questions:

- How do we model high electrification scenarios? One step that needs to be taken is to increase the flexibility of the global models regarding the final energy use. Also,

the interaction between different technologies like intermittent power production and electric vehicles or heat storages should be studied further.

- What is the role that models play in policy making and how do policy options influence model results?
- Can models and scenarios help us answer questions such as "If nuclear energy ends up not being expandable on a large scale, is electrification still possible?"

6. Summary

The discussion in the first session of the workshop concentrated on the challenges of **electrification of personal vehicles**, although electrification in the public transport and freight sectors should not be dismissed. Battery technology has issues with energy density and longevity. Fuel cells have a trade-off between cost and durability as well as issues with onboard hydrogen storage. There was also discussion about whether electric vehicles would change the traditional modes of vehicle use and ownership. There were many questions about the benefits and drawbacks of electric vehicles to the consumers and how consumer preferences might influence purchasing decisions. Charging infrastructure and the effect of new load on existing distribution and generation system was questioned.

Discussion about the **electrification of the heat production** concentrated on heat pumps. The status and economics of the technology were discussed. Rising fuel prices and technological progress are probably making the case for heat pumps stronger. There are encouraging improvements in heat pump efficiencies. In winter peaking regions, switching from fuel-based heating to heat pumps might create peak capacity problems. This could be alleviated with heat storage, but there needs to be economic incentives to do this, perhaps with real-time pricing. The development of smart meters and a smart grid is important to linking between electrification of transport and heat. Both can also provide ancillary services to the power system, which was one of the topics of the third session.

Electrification of transport and heat would require and cause changes in the **power systems and power markets**. New infrastructure would be needed, especially in the distribution of electricity, but the potentially more flexible load would also trigger changes in the generation of electricity. Electricity would behave more like a traditional commodity, if power systems had higher capability to store energy in different forms. Smart charging, V2G, and heat storages could also participate in the ancillary service markets in the power grid. This would offer additional revenue and help the power system to become more efficient. For all this to happen, enhanced cooperation between different stakeholders is required and further technological innovation would also help. More accurate pricing should promote preferred behavior and also provide an incentive for technological innovation. However, the behavior and preferences of consumers can be difficult to predict and it is not clear how much people would like to participate in programs that have the possibility to limit their energy use during high prices or if privacy might become an issue.

The workshop also tried to explore how **global energy models** handle the possibility of increased rate of electrification and the implications this might have for the electricity production. Global models are influential in the formation of international policy. Do the models have the necessary detail to be able to switch from fuels to electricity in transport and heating? There is also a complex interaction between additional load and

flexibility in the power sector and the ability to use larger amounts of intermittent low carbon power sources.

Follow-up cross-cutting research questions:

- What are alternative ways to get the benefits envisioned for increased electrification (namely, reduced CO_2 emissions from affected sectors, reduced oil imports, improved air quality, improved power-sector performance)?
- How do these alternative approaches to these ends compare to the increased electrification options considered here in potential contribution, cost, ancillary benefits, barriers, and potential for unwanted consequences?
- What are the system implications of the electrification approaches discussed here when they are considered together?
- How are the pace and scale of electrification going to be affected by various plausible schemes for limiting greenhouse-gas emissions?
- What are the other policies that are needed to maximize the benefits and minimize the costs and adverse impacts of electrification?

Photos courtesy of Martha Stewart

Appendix 1

ELECTRIFICATION OF ENERGY

Workshop Agenda
Wednesday, April 23, 2008
Venue: Allison Dining Room, 5th floor Taubman Building, HKS
Cambridge, MA

Use of electricity has been increasing faster than the use of energy for a long time. This trend could accelerate if the competitiveness of electricity in transport and heating continues to improve. Currently electricity accounts for a minor share of these major forms of energy end-use, but the potential for increased use of plug-in electric vehicles and heat pumps could change the picture. Meanwhile using fuels for transport and heating is getting more expensive and there is a growing recognition of huge alternative low-carbon resources (solar, wind and possibly geothermal and nuclear sources) from which electricity can be produced. Increased electrification of transport and heating would have profound implications for electricity policy, carbon dioxide emissions and the power system. These issues will form the agenda of this workshop. Hopefully, we will have informative discussions to provide food for thought for the participants as well as to clarify and shape a concrete research agenda for the future.

8:30-9:00 Breakfast

8:45 Welcome and Introduction
Kelly Sims Gallagher, Director, Energy Technology Innovation Policy

9:00-10:30 Session 1: Electrification of transport
Provocateur: Gustavo Collantes

The first part of the workshop will concentrate on the transport sector. The provocateur/moderator will introduce the topic and discussion will be conducted in a roundtable fashion. Questions will include: Are batteries and electric drive trains technologically ready? Will the economics for batteries and plug-in vehicles improve? Should car manufacturers concentrate on hybrids instead? How will carbon dioxide emissions be affected? Will there be a need to build an infrastructure for charging the vehicles, and if yes, at what point? What can be expected for car owner behaviour and what they might expect? How far can electrification go? Plug-in vehicles vs. smart growth? Are there hurdles in current legislation? Is there a need for subsidies to make the technology competitive and what policy measures would be preferable?

10:30-10:45 Coffee break

10:45-12:00 Session 2: Electrification of heat production
Provocateur: Juha Kiviluoma

Heat pumps, electric heat boilers and heat storage technologies could supplement traditional fuel-based heat production, if the costs are reduced. It is time to have a closer look at the status and competitiveness of these technologies. This will be a moderated roundtable discussion with the following questions: What limitations do heat pumps have with regards to efficiencies and heat temperature? What possibilities are there for cost reductions? Heat pumps in district heating? Heat pumps in industrial process heat? Heat pumps vs. electric heat boilers? Is there an incentive for heat storage? What could be done in cooling? If economics change, how fast adoption might happen? What institutional barriers are there for larger heat pump adoption? Is there a need for a FuturePump program to get experience with large scale heat pumps in different applications?

12:00-1:00 Lunch

1:00-2:15 Session 3: Power system and electricity markets
Provocateur: William Hogan

Plug-in hybrid vehicles and heat pumps with heat storage and demand response could provide ancillary services and a smoothing of the load duration curve. This would reduce the investment and operation costs of the power system per unit of energy. Who gets the benefit? Electricity consumption would increase. How would different parts of the power system handle that? How to deal with the uncertainty of available capacity? Does peak shaving with plug-in vehicles make sense? Will the power system get saturated with flexibility? Are there more benefits in a system with lot of variable wind and solar power or how high can penetration of variable sources go with the additional flexibility? Smart meters are being installed, should they be required to be compatible with plug-in vehicles? Should we be thinking about possible changes in market structures (i.e., how to reap highest possible benefit)? Who should regulate and oversee smart loading and V2G?

2:15-2:30 Coffee break

2:30-3:30 Session 4: Electrification in the global energy models and scenarios
Provocateur: Leo Schrattenholzer

Usually, global long-term energy scenarios do not study the electrification of the energy system specifically. Rather, electrification is a *result* of global energy models, based on trends and assumptions ("story lines"). The moderator will introduce the subject by summarizing the results of IIASA's scenarios – published at different times – with respect to the share of electricity in the future. The discussion should then include the following issues. What are the main parameters influencing the estimates? What are the respective roles of the demand side and of the supply side? How big is the renewable resource? What could the role of nuclear power be? What are the possible futures of transportation? How about heating? How global context differs from US context? What kind of research is needed to get more solid understanding of underlying issues? In which ways this could be a policy issue?

3:30-3:45 Coffee break

3:45-4:30 Session 5: Setting the agenda for research
Provocateur: John Holdren

Professor Holdren will summarize the workshop discussions and moderate a discussion on the key needs for further research. What are the areas with highest importance and largest uncertainty? How to share the work? Is there a need for continuing discussions around the theme? Implications for policy?

Appendix 2

List of Participants

NAME	TITLE	AFFILIATION
Jeff Alson	Senior Policy Advisor	US EPA, Transportation and Climate Division
K.R. Amarnath	Senior Project Manager, Energy Utilization	Electric Power Research Institute
Kevin Ball	Business Venture Developer, Distributed Energy	BP Alternative Energy
Audun Botterud	Energy Systems Engineer, Center for Energy, Environmental, and Economic Systems Analysis	Argonne National Laboratory
Bill Boyce	Electric Transportation Group Supervisor	Sacramento Municipal Utility District
Ashley Brown	Executive Director, Harvard Electricity Policy Group	Harvard University
Ananth Chikkatur	Research Fellow, Energy Technology Innovation Policy	Harvard University
Mark Ciolek	Vice President, Planning & Strategy	Exelon Corporation
Gustavo Collantes	Research Fellow, Energy Technology Innovation Policy	Harvard University
Paul Denholm	Senior Analyst	National Renewable Energy Laboratory
Robert Frosch	Research Associate, Science, Technology and Public Policy	Harvard University
Kelly Sims Gallagher	Director, Energy Technology Innovation Policy; Adjunct Lecturer, Harvard Kennedy School	Harvard University
Eckhard A. Groll	Professor of Mechanical Engineering	Purdue University
Britta Gross	Manager, Hydrogen & Electrical Infrastructure	General Motors
Phillip Harris	President and CEO (retired)	PJM Interconnection
Bill Hogan	Raymond Plank Professor of Global Energy Policy	Harvard University
John Holdren	Director of Science, Technology and Public Policy Program; Teresa and John Heinz Professor of Environmental Policy, Harvard Kennedy School	Harvard University
Tiina Koljonen	Senior Research Scientist	VTT Technical Research Centre of Finland
Juha Kiviluoma	Research Fellow, Energy Technology Innovation Policy; Research Scientist, Energy Systems, VTT Technical Research Centre of Finland	Harvard University
Henry Lee	Director of Environmental and Natural Resource Program; Lecturer in Public Policy, Harvard Kennedy School	Harvard University
Ludi Mahadi	Research Assistant, Energy Technology Innovation Policy; MPA Student, Harvard Kennedy School	Harvard University

Erich Muehlegger	Assistant Professor of Public Policy, Harvard Kennedy School	Harvard University
Bernard Neenan	Technical Executive, Power Delivery and Utilization	Electric Power Research Institute
Alan Nogee	Director, Clean Energy Program	Union of Concerned Scientists
David Raney	Senior Manager, Environmental and Energy Affairs	American Honda Motor
Steve Rosenstock	Manager, Energy Solutions	Edison Electric Institute
Ichiro Sakai	Assistant Vice President	American Honda Motor
Danilo J. Santini	Section Leader, Technology Analysis	Center for Transportation Research, Argonne National Laboratory
Dan Schrag	Director, Harvard Center for the Environment; Professor of Earth and Planetary Sciences	Harvard University
Leo Schrattenholzer	Senior Consultant	Integrated Resources Management
Michael Shelby	Chief Economic Analyst	US EPA, Office of Atmospheric Programs
A.J. Simon	Energy Systems Analyst, Global Climate and Energy Project	Stanford University
Mike Tamor	Executive Technical Leader, HEV&FCV Research	Ford Research and Advanced Engineering
Dean Taylor	Senior Technical Specialist, Electric Transportation	Southern California Edison
Jasna Tomic	New Fuels Program Manager	WestStart
Dawn Trammel	Chief Economist	Shell Energy North America
Tom Turrentine	Director, PHEV Research Center	Institute of Transportation Studies, UC Davis
Jon Wellinghoff	Commissioner	Federal Regulatory Energy Commission
Brett Williams	Ph.D. Graduate, Hydrogen Pathways Research Program	Institute of Transportation Studies, UC Davis
Bob Wimmer	National Manager, Technical and Regulatory Affairs, Energy & Environmental Research	Toyota Motor North America, Inc.
Audrey Zibelman	Chief Executive Officer	Viridity, LLC

This workshop report was prepared by Juha Kiviluoma and Gustavo Collantes. The interpretations of the presentations and remarks made in the workshop are the authors' alone. An electronic copy of this report is also available online at www.energytechnologypolicy.org.

Kiviluoma and Collantes, and Kelly Sims Gallagher of ETIP at Harvard University were the organizers of the workshop.

If you have any questions regarding this workshop please contact:

Dr. Kelly Sims Gallagher
Belfer Center for Science and International Affairs
Kennedy School of Government
79 John F. Kennedy St.
Harvard University
Cambridge, MA 02138
Tel: (617) 495-1960
Email: *kelly_gallagher@harvard.edu*
www.energytechnologypolicy.org