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February 27 2015

State of California Air Resources Board
Research Division
FY2015-2016 Research Plan Implementation

SUBJECT: Draft Proposal entitled "*Policy and Scenario Analysis for Managing and Mitigating California's F-Gas Emissions*"
UC Berkeley Principal Investigator: Professor Daniel Kammen
Period of Performance: 7/1/2015 – 6/30/2017
Amount of Request: $299,995
UCB Proposal Number 6795

To Whom It May Concern:

On behalf of the Regents of the University of California, we are pleased to submit the above referenced draft proposal to the to the California Air Resources Board in response to the FY2015-2016 Annual Research Plan solicitation.

Please note: An indirect costs rate of 10% has been included in this draft proposal on the assumption that any resulting award will contain terms that are consistent with the agreed upon Standard UC – ARB Interagency Agreement Terms. Should these terms not be used, an indirect cost rate of 25% would then apply which would increase the total amount requested.

The University representative to whom questions may be directed and with whom award negotiations may be conducted is Joyce So who may be reached at joyceso@berkeley.edu or at (510) 643-7365.

Contract and grant documents should be issued in the University's corporate name:
The Regents of the University of California
c/o Sponsored Projects Office
2150 Shattuck Avenue, Suite 300
Berkeley, CA 94704-5940.

Award documents that are sent electronically should be forwarded to spoawards@berkeley.edu.

Thank you for your consideration of this proposal.

Sincerely,

Joyce So

Joyce So
Contract and Grant Officer
Sponsored Projects Office

DRAFT PROPOSAL:

Policy and Scenario Analysis for Managing and Mitigating California's F-Gas Emissions

Principal Investigators: Daniel Kammen

Prepared for:

State of California Air Resources Board Research Division

PO Box 2815

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Berkeley, California 94720

February 27, 2015

Check if applicable:

Animal subjects ___na____ Human subjects ___na____

Contents

1. *Abstract*

This project will compare policy options for reducing F-gas emissions in the state from 2015 to 2050 and identify the optimal regulatory design and two "next-best" alternative control programs. The work will comprise four primary tasks each of which is described below.

(A) Information collection: A detailed literature review coupled with industry/vendor surveys and expert elicitation will help to define and delineate the current status/issues and prognosis for two key related areas: (1) technical specifications of emerging and existing low-GWP systems and barriers to adoption of such systems in technology, economics, and practical implementation factors ; and (2) existing regulatory policy designs drawn from related GHG and high GWP regulatory programs such as the European Union's F-Gas regulations of 2006 and 2015, including feasibility, enforceability, and potential economic impacts of key design features. The research team, in consultation with ARB will form a team of industry/expert advisors drawn from policy and technical experts that will provide expert inputs and review of all four key tasks and the research team may hold periodic workshops, listening sessions, and or surveys.

(B) F-gas Fee Program Analysis: This task will consider the potential approaches for an F-gas fee program and application of fee revenues. It will draw upon experience with fee-based and other high-GWP control programs to estimate the price elasticity of demand for F-gases and F-gas-intensive products/services. The research team will develop two complimentary models: a vintaging model and a life cycle cost model for the main sets of cooling equipment and other end uses, and this fee will be an input into the latter model. This modeling framework allows sensitivity to the fee amount and fee program design. The team will specify the parameters of the optimal fee program design, including point of regulation; fee basis, form and level; implementation mechanism; formula; and means for adjustment. Fee collection revenues and costs will be estimated and potential uses for the revenues will be discussed and prioritized by the research team.

(C) F-Gas Emission Reduction Optimal Policy Analysis: The team will evaluate an inclusive menu of policy options to determine the optimal mix of policies that can achieve 2030 and 2050 F-gas emission reductions, including sector-specific prohibitions, cap and trade variants, performance standards, deposit-refund schemes, targeted abatement and mitigation programs, as well as the fee program options specified in Part B, above. ARB staff will be consulted regarding legal authority or constraints and the team of industry/expert advisors will be consulted for their inputs and to review key assumptions. The optimal regulatory design and two "next-best" alternative control programs will be identified. Policy options will be clearly defined and evaluated using multiple criteria, including, but not limited to: net environmental impacts; reliability and verifiability of reductions; co-benefits, including health impacts; cost and cost-effectiveness; administrative and technological feasibility; economic impacts and their distribution; enforceability and the potential for emissions/economic leakage; and interaction with other regulatory programs and jurisdictions.

D. Final Report & Recommendations: The final report will integrate and summarize the findings and interim deliverables of the first three study activities. It will include a detailed presentation of the short-listed regulatory program designs and estimated impacts. A summary matrix of characteristics will be included for each policy.

2. Introduction

Ozone depleting substances (ODS), such as chlorofluorocarbons (CFCs) and other fluorine-containing gases (collectively known as F-gases) have been useful in many industries due to their low reactivity, low toxicity and low flammability. Emissions to the atmosphere of these substances can be released directly, such as from aerosols or fire extinguishers, or as leaks from refrigerators and air conditioners. Due to the high ozone layer depletion potential of these substances, their use has been phased out. The first phase substituted them with hydrochlorofluorocarbons (HCFCs), which have a significantly lower ozone depleting potential. These are also being phased out and replaced with substances that have zero ozone depleting potential. Many substances have been identified by the U.S. Environmental Protection Agency's (USEPA) Significant New Alternatives Policy Program (SNAP) as alternatives for nearly all applications (USEPA, 2012). Unfortunately some of these substitute substances, especially hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) have a significant global warming potential and are referred to as high global warming potential (GWP) gases. For instance, HCFCs have a mean GWP of 700, while HFCs have a mean GWP of 950 but can be as high as 1300;[1] by definition, CO_2 has a GWP of 1.

High global warming potential (GWP) refrigerants in California are projected to increase to almost 43 million metric tons (Mt) of CO_2-equivalent emissions (CO_2e) in 2050 or nearly 45% of the 85 Mt CO_2e total state greenhouse gas (GHG) goal for 2050. Unless this critical segment of "non-energy" emissions is brought under control and sharply reduced, this sector alone may prevent the State from achieving its long-term climate goal. The sector is dominated by two end uses: refrigeration and air conditioning (RAC) but a diverse set of other applications also contribute emissions (foam insulation, gas-insulated switchgear (GIS), semiconductor processing gases, aerosols, and fire extinguishers). For many applications, a cost effective low GWP refrigerant is available today. However, the slow turnover of equipment, lack of incentives, and lack of familiarity with new systems are all barriers to widespread adoption of low GWP equipment. For example, the slow increase in the number of new stores with new refrigeration equipment, and the long duration between major store renovations that can provide opportunities to install new alternative-technology equipment, adds to the urgency of developing data-based and systematic assessments of low-GWP refrigeration systems. For example, waiting until 2025 or 2030 to embark on a large-scale effort to move away from existing refrigeration systems may not provide enough lead time to intercept the fleet of installed systems, or may sharply increase the costs to meet 2050 climate targets if for example, "forced replacement" of equipment is required.

This proposed analysis aims to provide the state with a systematic policy analysis of F-Gas emission reduction strategies to help enable the Air Resources Board (ARB) and other state policymakers to develop optimal plans and policies to mitigate the climate impacts in the high GWP sector and to reduce high GWP emissions to roughly 90% of business-as-usual 43 $MMTCO_2e$ in 2050. For example, business as usual HFC refrigerants but with much tighter leakage and disposal requirements can be compared to an aggressive phase out of high GWP and transition to low GWP refrigerants in terms of overall GHG savings and overall policy costs. This project will build two models to evaluate policy options: a stock vintaging model and a lifecycle cost model for RAC equipment types for both conventional HFC and alternative low

[1] Although CFCs and HCFCs also have high GWPs, they are not required as part of inventories, as they are being phased out under the Montreal Protocol. Therefore there contribution to greenhouse gas emission in 2050 is projected to be zero.

GWP refrigerants. Scenario analysis will be conducted to estimate future "refrigerant demand", e.g.: appreciable global warming in summer months boosting AC demand; greater decarbonization of the water heating sector through heat pump based water heating and cleaner electricity; and faster or slower economic growth. This modeling framework will then be the basis for evaluation of policy options such as F-gas fee collection, sector specific prohibition, performance standards, and others pertinent to each strategy. Particular emphasis will be given the F-gas fee collection strategy and its interaction with other downstream GHG policies.

Each of the policy options will be evaluated by multiple criteria: estimated emission reductions and co-benefits; cost, cost-effectiveness; feasibility; economic impacts and their distribution; enforceability and the potential for leakage; and interaction with other (state, federal, international) regulatory programs. Metrics will be created for each or all of the criteria (e.g., integrated costs over the 2015-2050 timeframe for individual items; "spider-plots" to illustrate policy assessment vs. a collection of metrics, etc.).

The objective of this project is to compare and contrast the relative strengths and weaknesses of competing F-gas reduction policies. The modeling framework will allow sensitivity analysis for each policy and better enable policy makers to understand the landscape and apply the most technically viable, cost effective, and "operationally efficient" F-gas reduction policies.

Table 1 shows the policy imperatives for today's alternative refrigerants compared to the Montreal Protocol phase out in the late 1980s. Two additional technical and policy imperatives have been added to the MP constraints: the need for low GWP gases or materials and the need for equivalent energy efficiency to conventional high GWP gases or materials.

Table 1. The policy imperatives for today's alternative refrigerants compared to the Montreal Protocol phase out in the late 1980s.

Refrigerant Property	Montreal Protocol (1980s) Policy and Technology Imperatives	Current Policy and Technology imperatives
Ozone Depletion Potential	Non-ODS	Non-ODS
Material Safety	Non-flammable, non-toxic substance desired	Non-flammable, non-toxic substance desired
Global Warming Potential	Not a focus area	**Low GWP**
System Energy Efficiency	Not a focus area	**Energy efficiency level at or above conventional refrigerant**

Schwarz et al. (2011) provides a comprehensive account of F-gas policies in the European Union, including 2006 regulations, costs of mitigation measures such as improved leak detection, and alternative low GWP refrigerants by end use application. This study assumes that systems with alternative refrigerants achieve the same or better energy efficiency as conventional refrigerants, but while this is true for some refrigerants e.g., propane in smaller refrigeration units, this is not always the case.

A projection of California emissions from F-gases to 2050 is provided by Gallagher et al. (2014) using updated appliance end-of-life "survival curves. " Current emissions by sector and end use are estimated. Gallagher et al. (2014) considers refrigeration, chillers, unitary and residential air conditioning and transport refrigeration units and refrigerated shipping containers. Total loss in annual leakage and refrigerant loss at equipment end-of-life is found to be over 10 million kilograms of refrigerant charge, of which 49% is from stationary AC equipment, 45% from refrigeration, 4% chillers, and 2% transport related.

Wei et al. (2014) provides detailed estimates for F-gas emissions in various sectors in 2050 as well as key mitigation measures by sector that can be taken to reduce F-gas by emissions. Both Wei et al. (2014) and Gallagher et al. (2014) project F-gas emissions to reach nearly 50 MMtCO$_2$e by 2050 and the former report estimates a technical potential reduction of almost 90% of business-as-usual (BAU) emissions is possible by 2050.

The U.S. EPA has a number of relevant publications regard F-gas emissions and mitigation measures[2]. EPA 2013 has an extensive list of cooling equipment lifetime, leakage rates, alternative refrigerants or chemicals, and market penetration rates. Other reports describe cost and benefits of proposed measures to reduce equipment leakage rates. The Significant New Alternatives Policy (SNAP) Program is EPA's program to evaluate and regulate substitutes for the ozone-depleting chemicals that are being phased out. New SNAP rules recently released in the second half of 2014 designates some natural refrigerants acceptable subject to use conditions subject to use conditions pending further review, for retail food refrigeration, household refrigerators and freezers and residential and light commercial AC and heat pumps.

Recent studies have considered the performance and cost impacts of moving from high GWP refrigerants in air conditioning equipment (such as R-410a) to lower GWP refrigerants such as hydrofluoro-olefin (HFO) blends and hydrocarbons. Refrigerants in use today for new equipment are typically HFCs, which are non-ozone depleting substances but unfortunately have high GWP, e.g., equivalent warming potential of thousands of times that of CO_2. The GWP and composition of R-410a and some alternative lower GWP refrigerants are shown in Table 1. Thus, for equipment with high refrigerant charge, and high charge leakage or high end-of-life refrigerant loss, a shift to lower GWP refrigerants can provide much lower lifetime GHG emissions. Globally, there is movement to enact treaties or global agreements that mandate a transition to lower GWP refrigerants (e.g., White House, 2013). The timing and content of such regulations vary with the type of cooling equipment and the country or region of the world. Still, a more comprehensive technical and economic understanding of the impacts of switching to alternative refrigerants is needed. For example, the American Heating and Refrigeration Institute (AHRI) has begun a

[2] Proposed SNAP changes can be assessed at: http://www.epa.gov/ozone/downloads/SAN_5750_SNAP_Status_Change_Rule_NPRM_signature_version-signed_7-9-2014.pdf. Costs and Benefits of Proposed Measures to Reduce Refrigerant Leaks from Commercial Refrigeration Systems can be accessed at: http://www2.epa.gov/sites/production/files/documents/Supermarket_Refrigerant_Leak_Reduction_Measures_cost-benefit_9_15_11.pdf.

voluntary collaborative testing program to evaluate the performance of various refrigerants and reduce the time and costs associated with developing alternative refrigerants for different applications, but full economic analysis is yet to be characterized.

Note that for alternative air conditioning refrigerants, there are currently no replacements that have both single digit GWP values and A1 safety classification[3] (lower toxicity and non-flammable), and there are no low-GWP drop-in replacements for R-410a. For example, the two chiller alternatives either have a GWP > 500 (XP-10) or are slightly flammable (R-1234ze(E)). The three representative alternative refrigerants for air conditioning (DR-5, R-32, and L-20) have GWPs ranging from 295 to 716. However, these blends are likely to be classified as A2L (low toxicity, low flammability) and would therefore probably require special design and safety features. R-410a and R-134a by contrast are classified as A1 (lower toxicity, non-flammable). Thus any modeling of R410a replacement would have to take these considerations into account.

Table 2. R-410a and alternative refrigerants[4] global warming potential and composition.

Refrigerant	Net GWP (100 year)	Composition	Safety Classification	Sources
R-410a	2088	Mixture of difluoromethane (CH_2F_2, called R-32) and pentafluoroethane (CHF_2CF_3, called R-125) 50% CH_2F_2/50% CHF_2CF_3	A1	E
R-134a	1430	CH_2FCF_3: 1,1,1,2-tetrafluoroethane (HFC-134a)	A1	a, b
R-1234yf	4	$CF_3CF{=}CH_2$: 2,3,3,3-tetrafluoropropene (HFO-1234yf)	A2L	C
OpteonTM XP-10	631	R-134a/R-1234yf blend (44%/56% mass percentage)	A1	D
R-1234ze(E) (HFC-1234ze(E))	6	1,3,3,3-Tetrafluoropropene ($C_3H_2F_4$)	A2L	e,f
N13a	604	HFC-134a/1234yf/1234ze blend (42%/18%/40% mass percentage)	A1	D
R-290 (HC-	3.3	Propane	A3	d, e

[3] The ASHRAE safety classification for refrigerants is as follows: refrigerants classified as "A1" are lower toxicity and non-flammable; those classified as "A2L" are low toxicity and low flammability, and those classified as "A3" are lower toxicity and higher flammability.
[4] This is not an exhaustive list of refrigerants and other blends are being considered as well, depending on the application, performance, and operational requirements of the cooling system under consideration.

290)				
R-600a	<20	Isobutane	A3	D
DR-5	490	R-32/R-1234yf mixture (72.5%, 27.5% mass percentage)	A2L	D
R-32 (HFC-32)	716	Difluoromethane (CH_2F_2)	A2L	F
L-20	295	HFC-32/HFC-152a/HFC-1234ze(E); (41.5%/10%/48.5% mass percentage)	A2L	F

(a) http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html, accessed 2 July 2014
(b) http://www2.dupont.com/Refrigerants/en_US/assets/downloads/h47751_hfc134a_thermo_prop_eng.pdf, accessed 2 July 2014
(c) http://www.nedo.go.jp/content/100080127.pdf, , accessed 2 July 2014
(d) http://www.unep.org/ozonaction/Portals/105/documents/webinar/2013/14August2013_Ppt_Karim%20Amrane.pdf, accessed 2 July 2014
(e) http://en.wikipedia.org/wiki/List_of_refrigerants; accessed July 17, 2014
(f) UNEP 2013, Report Of The Technology And Economic Assessment Panel, September 2013, Volume 2 Decision XXIV/7 Task Force Report Additional Information To Alternatives On ODS

An illustration of the increasing importance of the F-gas sector is given in Figures 1 and 2 below. Based on a recent study by Nelson et al. (2014), electricity sector carbon intensity may need to be reduced by greater than 80% to achieve the state's 80% GHG reduction target. If this occurs, the total lifetime GHG emissions from cooling equipment such as commercial unitary air conditioning equipment will flip from the current scenario of being dominated by indirect emissions from power consumption to direct emissions from refrigerant lifetime leakage.

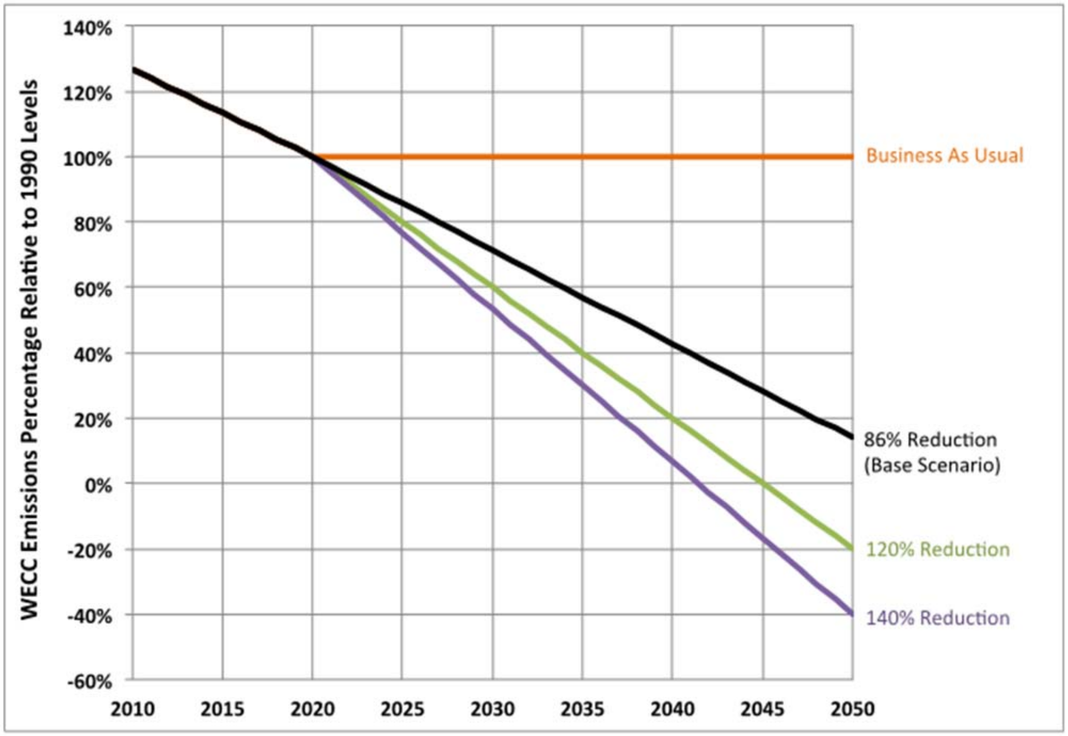

Figure 1. Example electricity sector scenarios based on a tightening carbon cap for overall electricity sector emissions. The BAU scenario assumes 100% of 1990 emissions levels in 2020 and beyond. Base scenario has a linear decrease to 86% below 1990 emissions levels in 2050. (Note that the decarbonization of electricity is thought to be relatively "easier" on a technical and cost basis than for other sectors such as transportation, thus the base scenario is greater than 80% emissions reduction.) (Nelson et al., 2014)

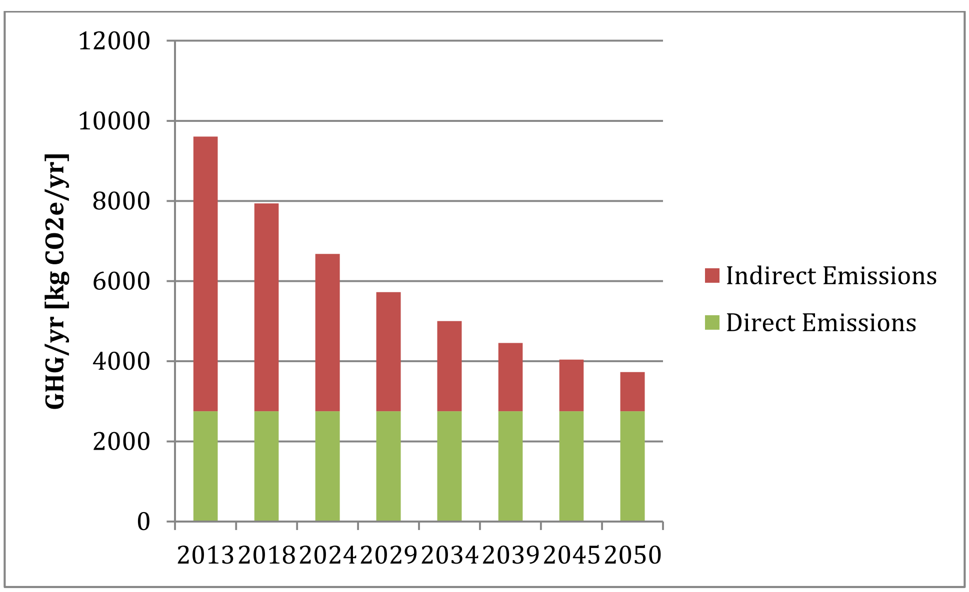

Figure 2. Annualized GHG emissions for a new commercial unitary air conditioning unit, illustrating that as the electricity supply system becomes cleaner in carbon intensity, the fraction of direct emissions from

refrigerant loss becomes the dominant source of GHG emissions. (Assumptions: CUAC has 15 year lifetime, R410a refrigerant, 15 ton cooling capacity, 19.8kg refrigerant charge at beginning of life, 1523kWh/ton electricity consumption per year, 100% lifetime leakage assumption, 86% reduction in electricity carbon intensity as in Figure 1, and 300g CO_2e/kWh electricity carbon intensity in 2013.)

3. Project Objectives

This project will provide an in depth analysis of fee-based policy for F-gas emission reduction toward meeting the 2030 and 2050 targets. The project will also provide a comparative analysis of a wide range of policy instruments including fee-based programs, cap and trade, performance based standards, voluntary programs, etc. The research team will propose a leading policy and two next best policy alternatives. The project will be beneficial to ARB by providing important policy guidance and quantitative modeling for F-gas emission reduction required for meeting 2030 and 2050 climate goals and will also help answer the following questions:

- What are relative advantages and disadvantages of fee based program vs other policy instruments?
- How does the policy recommendation change as a function of key assumptions such as technological availability and system costs with a new refrigerant?
- How do various policy instruments compare to each other across a wide range of policy criteria?
- What is the relative cost and GHG savings of tight leakage loss regulations vs. greater adoption of low GWP ref gases?
- How much can F-gas emissions reduced with cost effective measures in 2030 and 2050?

4. Technical Plan

(A) Information collection

This task will consist of the following key tasks. For many of these tasks, literature and American Heating and Refrigeration Institute (AHRI) sources, expert elicitation and stakeholder inputs will be utilized.

- Goal definition – the team will propose an overall F-gas reduction target for 2030 and 2050, e.g., 2/3 HFC reduction from 2010 by 2030 and 90% reduction by 2050, in consultation with ARB.
- The F-gas ecosystem will be delineated as in Figure 3 below will be described to identify key stakeholders.
- Set up structured process for expert – although this will not be an official policy regulation or standards rule-making, the research team will make an effort to define a structured process for expert and stakeholder inputs.
    - Stakeholder inputs will be requested with clear timelines.
    - Listening sessions and/or survey frameworks will be defined early on in the project.
- Key constraint identification – the team will identify key constraints to F-gas mitigation and policy measures e.g. costs, safety, health/environment, equivalent energy efficiency for systems with new refrigerants, etc.
- Key barriers will be highlighted – e.g., the lack of "drop-in" refrigerants for R-410a, the need for increased safety and or containment of slightly flammable alternative refrigerants, the need for demonstration and/or pilot programs for risk mitigation.
- Drivers of demand will be identified in terms of key sectors, equipment types, and growth rates, based on data from Gallagher et al, 2014 and Wei et al. 2014. Additional "worst case" demand will be considered along two axes: global warming leading to greater ambient temperature and greater air conditioning demand; and the scenarios from Wei et al. 2014 where a large portion of heating demands are electrified with heat pump based heating.
- Technology readiness and roadmap
    - Potential Low GWP replacement refrigerants and technologies will be mapped.
    - Emerging technologies for leak detection and management and recovery and destruction of F-gas banks will be researched and enumerated.
- Define baseline condition- F-gas sector characterization
    - e.g. HFC banks and insulation foam banks as in Wei, et al, 2013
    - ARB- Gallagher 2013 provides one helpful baseline assessment
    - All "baseline" or BAU policies will be listed and described.
- Abatement cost estimates will be compiled
    - Sources include EU supporting documents for 2006, 2015 F-gas regulations (Schwarz et al. 2011), EPA sources, engineering estimates, as well as expert elicitation
    - A marginal abatement cost curve will be generated.
- Benchmarking of regulatory policy design
    - Key policy insights and learning will be summarized from related programs from across the globe (e.g. EU regulations, Australia, Japan, etc.)

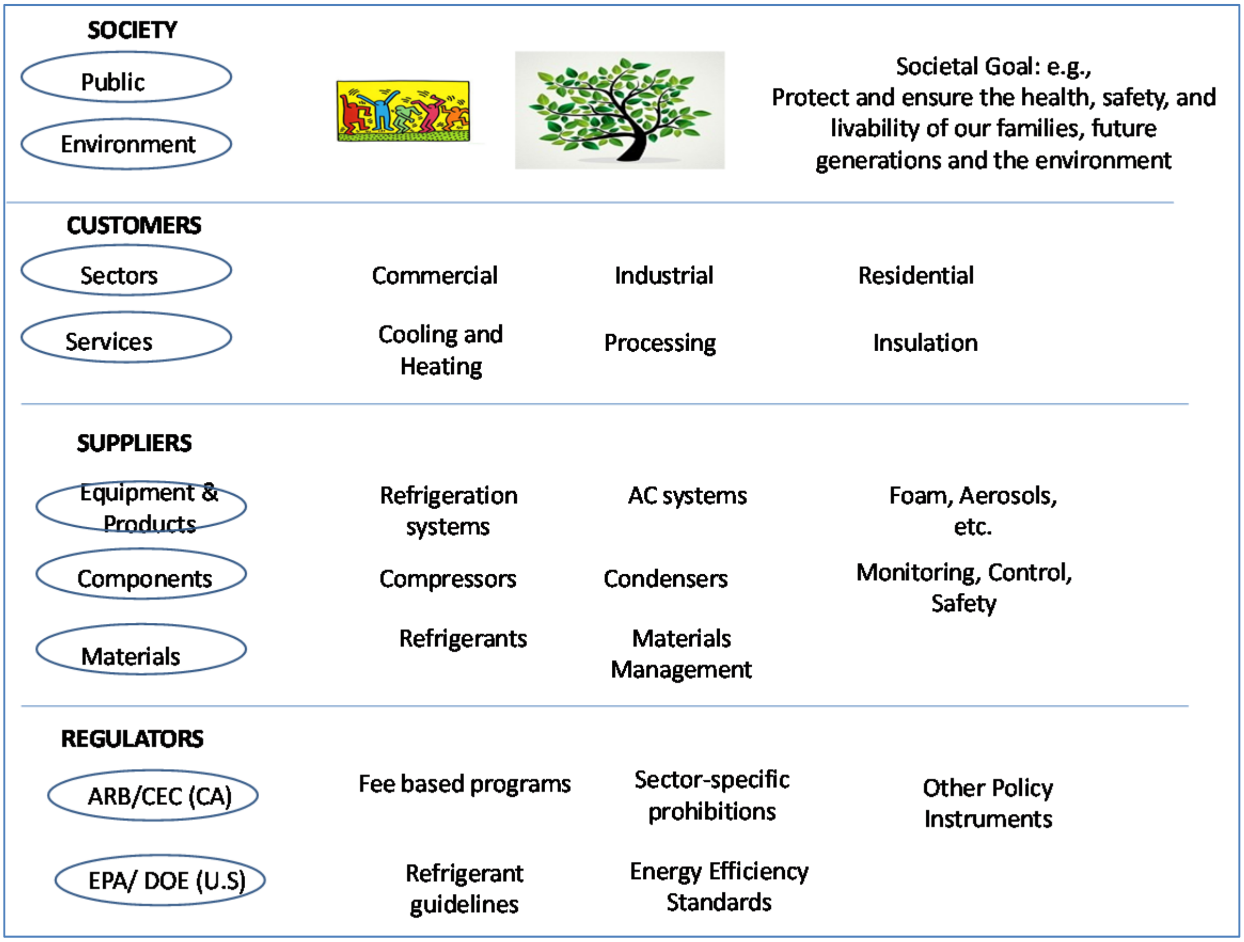

Figure 3. Representation of F-gas ecosystem will help to identify key stakeholders such as equipment suppliers, commercial and industrial sectors, and refrigerant suppliers.

(B) F-Gas Fee Program Analysis

The 2014 CPUC Scoping Plan update states the following for high GWP policy options: "an upstream fee would ensure that the climate impact of these substances is reflected in the total cost of the product, encouraging reduced use and end-of-life losses, as well as the development of alternatives. The fee would be variable and associated with the impact the product makes on public health and the environment. This could encourage product innovation because fees would correspondingly decrease as the manufacturer or producer redesigned their product or found lower-cost alternatives. This mitigation fee would complement many of the downstream high GWP regulations currently being developed."

HFC reductions address a global reduction problem (GHG causing global warming) but can interact with localized impacts insofar as localized power supply may be affected through either less or more electricity consumption associated with transitioning to alternative refrigerants. Here we treat the F-gas problem primarily as a global commons problem because of the constraints shown in Table 1, and since the electricity supply in California is relatively clean from a carbon intensity perspective and becoming cleaner over time.

The policy analysis will be informed by a vintaging model and life-cycle cost analysis for refrigeration and AC equipment (Figure 4) with simplified treatment for other product types (foam, fire extinguishers, high voltage switchgear, etc.) with modeling detail commensurate with the refrigeration/air conditioning (RAC) end uses being the dominant fraction of high GWP F-gas emissions. Since there are a multiplicity of refrigeration and AC equipment, a subset of key equipment types will be modeled for each end use. For example, AC will be modeled by 5-6 product categories (commercial unitary AC, chillers, residential AC, window units, etc.). Vintaging analysis will utilize assumptions and inputs from ARB's stock modeling the EPA's vintaging model wherever possible.

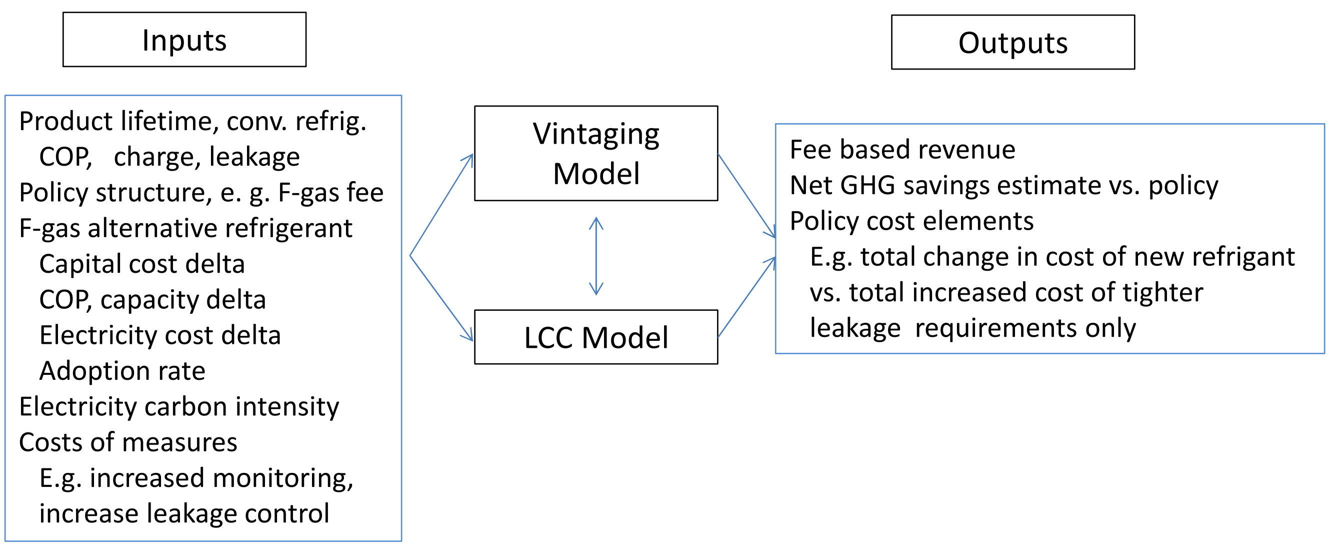

Figure 4. Policy impacts will be informed and by a vintaging model and LCC modeling for end use i and product type j for current HFC refrigerants and alternative refrigerants.

Data will be collected for both systems with baseline HFC refrigerants and for systems with alternative refrigerants. These data sets will then serve as inputs for the LCC calculation. For example, a vintaging model combined with the leakage loss (both annual and end of life) can help to determine the overall revenue in a fee-based program, while a gradual prohibition of high GWP baseline refrigerants with transition to alternative low GWP refrigerants can give the total GHG savings and costs versus a baseline case without any prohibition of high GWP refrigerants.

LCC costs will be drawn from the literature, and Department of Energy appliance standards technical support documents (TSD). LCC costs consist of the components shown in Table 3 below. In particular a shift from a conventional HFC refrigerant to an alternative low GWP refrigerant could incur changes in many of the cost components as shown in the table. This type of analysis can be quite complex and involved for a given end use. For example, detailed modeling could be done for energy consumption –

including climate zone dependence, component dependence, energy efficiency distribution by product models, etc. For this policy-focused analysis, a balance will be made between technical modeling precision and completeness versus consideration of a broad range of policy instruments, costs, and, policy impacts. Thus, simplifying assumptions will be made for LCC inputs such as capital cost and energy consumption. Energy (electricity) costs may be assumed to be shifted by the range of nominal amounts of COP shifts reported in testing data for a new refrigerant. The most recent data from the literature and AHRI will be utilized. Where capital cost impacts are not known, best estimates will be made based on expert elicitation and known dependencies of alternative refrigerant type and cooling capacities. Data uncertainty will be explicitly noted and costs vs input assumptions will be the subject of detailed sensitivity analysis to key cost input assumptions.

Table 3. Typical life cycle cost (LCC) components for RAC equipment. (COP = coefficient of performance). Components marked with an asterisk are assumed to be different for alternative refrigerants compared to conventional high GWP refrigerants.

LCC Cost Component	Examples
Capital cost/ depreciation (*)	Equipment cost/lifetime, monitoring
Maintenance cost	Inspections
Parts cost, consummables (*)	Refrigerants, oils
Energy cost (*)	COP, Electricity prices
Disposal, recovery costs (*)	Refrigerant recovery policy

This work will consider the potential approaches for an F-gas fee program and application of fee revenues. It will draw upon experience with fee-based and other high-GWP control programs to estimate the price elasticity of demand for F-gases and F-gas-intensive products/services. The research team will develop two complimentary models as described above – a vintaging model and a life cycle cost model for the main sets of cooling equipment and other end uses, and this fee will be an input into the latter model. This modeling framework allows sensitivity to the fee amount and fee program design.

The team will specify the parameters of the optimal fee program design, including point of regulation; fee basis, form and level; implementation mechanism; formula; and means for adjustment. For example, calculation of LCC costs will give an indication of how high the fee must be set to constitute a large amount relative to other lifetime costs. Fee collection revenues and costs will be estimated and potential uses for the revenues will be discussed and prioritized by the research team, e.g. further research, mitigation, fee and dividend, demonstration programs, etc.

Both F-gas fee collection and distribution program options should be evaluated by multiple criteria, including:

- o Estimated emission reductions and co-benefits;
- o Cost, cost-effectiveness;
- o Feasibility;
- o Economic impacts and their distribution;
- o Enforceability and the potential for leakage;
- o Interaction with other (state, federal, international) regulatory programs.

Key pro and con analysis of fee-based programs will be conducted and will include the following critical considerations:

- The fee basis – a wide range of topics including fee basis on refrigerant GWP vs lifetime direct GHG , the fee schedule – ramped up in time, etc.; the fee amount vs availability of a cost effective alternative will be analyzed.
- The fee may want to offer rebates for reclaimed refrigerant, but refrigeration reclaim can be a complex process.
    - If the scheme intends to enhance reclamation and destruction in specialized facilities as opposed to venting of used gases, sums needed for tax rebates may need to increase over time.
- Fee assessment. Who pays? The producer or the user?
    - Consideration here will include the degree of market power for the upstream monopolist refrigerant supplier – a fee or tax on the refrigerant may either mitigate the degree of price discrimination depending on market organization of sellers and buyers.
    - Enforceability and potential for leakage will be examined. Attention should be given to imports of used F-gases from other which might not have been placed on the national market and were hence not subject to fees before. Fees on virgin sales of F-gases would not address F-gases in imported products which may disfavor domestic equipment. A fee on F-gases in manufactured products could address emissions from imported appliances.
- The fee program's operational/ implementation plan, administration and control costs will be elucidated. Interaction with other programs will be relevant here, in case any other programs would be able to share the implementation cost burden. Feasibility will be assessed.
- Comparison with other fee-based programs in the EU-27 and other part of the world e.g., Australia.
    - Fee schedule in Slovenia
    - Tax in Norway with reimbursement for delivery/destruction but impact not clear
- Exemptions from any fee or tax should be chosen carefully and not be not so broad as to undermine the intent of the regulation. Economic impacts and their distribution will be assessed.
- The level of fees needs to be determined and should be flexible enough to provide regular adjustments to the economic situation. The means for adjustment will be explored and specified.
- Price elasticity for F-gases will be assessed. However "as many patents for HFC production recently expired, production in Asia is strongly increasing and HFC producers may react with price decreases for HFCs to counterbalance the effects of new taxes introduced in order to keep HFC production competitive relative to alternative substances" (Schwarz et al., 2011). This may make it challenging to assess price elasticity for F-gases in the context of the future development of global markets with significant growth projections of production levels in Asian countries.
- Assess the risk associated with setting the fee too low due to uncertainty in the price of these products and the supplier market.
- Expert elicitation. This may include a survey framework depending on ARB inputs to survey key stakeholder identified from Figure A above (suppliers and customers) on the impacts of a proposed fee, fee amount, fee schedule, etc.
- Policy linkages and interactions with other policies e.g., waste regulations and safety and GHG reduction

- Fee collection revenues and costs will be estimated and potential uses for the revenues will be discussed and prioritized by the research team, e.g., monitoring and verification vs dedicating revenue to further R&D or leakage mitigation measures.
- A broad set of fee based policies will be drawn for comparative analysis from across the world (Denmark, Norway, Australia, Slovenia, etc.) and key learnings from each policy example will be given as they pertain to the above considerations.

Interim Deliverable: F-gas Fee Program Analysis findings and recommendations.

(C) Evaluation of other policies

Each of the policy options will be evaluated by multiple criteria: estimated emission reductions and co-benefits; cost, cost-effectiveness; feasibility; economic impacts and their distribution; enforceability and the potential for leakage; and interaction with other (state, federal, international) regulatory programs. Metrics will be created for each or all of the criteria (e.g. integrated costs over the period 2015-2050 for individual items; "spider-plots" for the collection of criteria, etc.). An example policy ranking template is shown in Table 4. For each of the items shown in Table 4, the research team will add metrics (qualitative and/or quantitative) and then a ranking such as "high", "medium" and "low".

Table 4. Example policy ranking template (from UNEP 2004)

Policy parameter	Option review*	Ranking* (H,M,L)
Description		
Main policy		
Choices re: distribution of initial rights, ability to transfer, duration and caps		
Performance		
Environmental efficacy		
Complexity		
Cost of implementation and operation		
Anticipated side-effects		
Social: highly impacted groups (exposure, job loss, increased poverty)		
Short-term economic impacts		
Long-term economic impacts		
Trade and competitiveness impact		
Proposed flanking measures		
Feasibility		
Institutional capability to implement?		
Powerful opposition?		
Other factors of interest/concern		

*Each of the final policy options should have its own review and ranking columns.

Where possible, the modeling framework of Fig. 4 above will be used to assess the costs of each proposed policy. Where this is not possible to do quantitatively, either qualitative relative assessments of each policy will be provided, or expert elicitation will be sought. One particular comparison to be made is the following: what is the relative cost and GHG savings of tighter leakage loss regulations vs. greater adoption of low GWP refrigerant gases?

Market instrument concerns have been summarized by Stavins (2001) as follows and these will be additional guidelines in evaluating policy options:

1. Cost variance –a large range of abatement costs favors market instruments versus command and control regulations
2. Pollution mixing resulting in hot spots – this is not an issue for HFCs since they are a pollutant to the global atmosphere as discussed above.
3. Policies are dependent on cost/benefit patterns. For example, for very uncertain marginal abatement costs, a quantity-based instrument may be preferred. The uncertainty in the factors shown in Table 1, for example, may suggest a quantity-based instrument is preferred.
4. Responsiveness to policy – consideration is needed for rapid economic growth, price inflation, and exogenous technological change. For example, the team will explore prospective learning curves for refrigeration and air conditioning technologies to project further cost reductions and technological progress.
5. Transaction costs – these can be low in principal if properly designed policy, but the research team will consider these in some detail in terms of the implementation and operational considerations of each policy.
6. Self – identification to claim permits may be a benefit for cap and trade programs with allocation of permits.
7. Political feasibility

Distributional concerns will also be considered. Sensitivity analysis will be done for key changes in refrigerant demand. Global warming may drive more summer AC demand and/or higher refrigerant demand may result from electrification of water heating or space heating to heat pump-based heating in conjunction with lower carbon-electricity supply. These dependencies may shift the resultant recommendation from one set of policies to another set.

Given that the scope of this project demands many data inputs—many of which will be drawn from disparate sources using different methods of synthesis and collection (e.g., engineering estimates, survey data, expert consensus, etc.)—this project will develop and employ a rating scheme for documentation of data quality. The rating scheme will be based on a review of data quality screening methods, such as that employed by Junilla and Horvath (2003) which rates modeling input data based on such factors as technological, temporal, and geographic relevance and source method. Based on this scheme, the user model will contain a master summary of data quality for all major parameter assumptions so that users can assess data quality and gaps and improve data quality over time.

Applying transparent criteria and assumptions as detailed above, the research team will systematically compare F-gas emission reduction policy options to identify the policy or combination of policies that offers the optimal approach to achieving targeted 2030 and 2050 F-gas emission reductions. ARB staff will be consulted regarding legal authority or constraints. As above, a broad set of policy examples will be drawn for comparative analysis from across the world (F-gas, cap and trade, high GWP prohibitions, etc.) and key learnings from each policy example will be given as they pertain to the above considerations. The optimal regulatory design and two "next-best" alternative control programs will be identified.

Interim deliverable: F-gas policy scenario analysis findings.

(D) Final Report and Recommendations

The final report will integrate and summarize the findings and interim deliverables of the first three study activities. It will include a detailed presentation of the short-listed regulatory program designs and estimated impacts. A summary matrix of characteristics will be included for each policy. All assumptions, calculation factors, and formulas used will describe in sufficient detail for an independent reviewer to arrive at the same calculated results.

Deliverable: Final report and recommendations

5. Facilities and Technical Team

Daniel Kammen (Principal Investigator) is the Class of 1935 Distinguished Professor of Energy with appointments in the Energy and Resources Group, The Goldman School of Public Policy, and the Department of Nuclear Engineering at the UC Berkeley. Daniel Kammen is the Class of 1935 Distinguished Professor of Energy with appointments in the Energy and Resources Group, The Goldman School of Public Policy, and the Department of Nuclear Engineering at the University of California, Berkeley. Dr. Kammen directs the Renewable and Appropriate Energy Laboratory (RAEL) and the Transportation Sustainability Research Center (TSRC). During 2010 – 2011, Dr. Kammen served as the first Chief Technical Specialist for Renewable Energy and Energy Efficiency. He now serves as a Fellow of the U. S. State Department's Energy and Climate Partnership for the Americas (ECPA).

Dr. Kammen directs research programs on energy supply, transmission, smart grid and low-carbon energy systems, life-cycle impacts of transportation options and land-use planning, and on energy for community development in Africa, Asia, and Latin America. He is a coordinating lead author for the Intergovernmental Panel on Climate Change (IPCC), which won the Nobel Peace Prize in 2007. Dr. Kammen also serves on the National Technical Advisory Board of the U. S. Environmental Protection Agency. Dr. Kammen is the author of over 300 journal publications, 4 books, 30 technical reports, and has testified in front of State and US House and Senate committees over 30 times.

Masters of Public Policy graduate students (2) from Goldman School of Public Policy, University of California Berkeley (to be determined)

Consultant/ Expert elicitation is planned and may include the following experts, among others:

Douglas C. Scott, President, VaCom Technologies, for new technology for supermarkets and refrigerated facilities; **EOS Climate Systems** for refrigerant disposal technology and incineration costs, and **Hung Pham** of Emerson Technologies, for refrigerant consulting and compressor performance.

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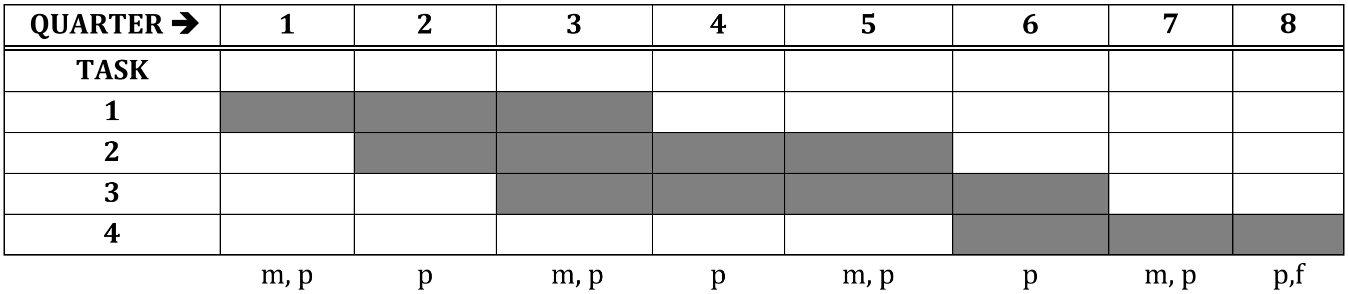
7. Project Schedule



m = Meeting with ARB Staff
p = Quarterly progress report
f = Deliver final report

Task	Description	Project Deliverable
1	Information Collection	A report summarizing of findings, abatement cost estimates, F-gas sector characterization, technology assessment, and example regulatory policy designs and learning from examples from around the world.
2	F-Gas Fee Program Analysis	F-gas fee program analysis findings and recommendations. A report containing text, tables or spreadsheets of collected data and all policy analysis and recommendations.
3	F-Gas Emission Reduction Optimal Policy Analysis	F-gas scenario analysis findings. A report containing text, tables or spreadsheets of collected data and all policy analysis and recommendations.
4	Final Report and Recommendations	A report containing text, tables, or spreadsheets of the data analysis. All assumptions, calculation factors, and formulas used will described in sufficient detail for an independent reviewer to arrive at the same calculated results.

8. Estimated Cost by Tasks

Task	Labor	Employee Fringe Benefits	Equipment	Travel	EDP	Copy & Print	Mail, Phone, Fax	Materials and Supplies	Analyses	Misc	Overhead	Cost by Tasks
1	$37,473	$16,578	$0	$250	$0	$120	$190	$400	$0	$337	$4,500	$59,848
2	$74,946	$33,157	$0	$250	$0	$240	$380	$800	$500	$675	$9,000	$119,948
3	$56,210	$24,868	$0	$250	$0	$180	$285	$600	$500	$506	$6,750	$90,149
4	$18,737	$8,289	$0	$250	$0	$60	$95	$200	$0	$169	$2,250	$30,050
TOTAL	**$187,366**	**$82,892**	**$0**	**$1,000**	**$0**	**$600**	**$950**	**$2,000**	**$1,000**	**$1,687**	**$22,500**	**$299,995**

Budget Justification

UCB Composite Benefit Rates (effective 7/1/2014)
The following composite campus benefit rates for the UC Berkeley campus are now in effect, and will be charged to sponsored projects.

	Approved	Projections for Planning Purposes ------------>				
CBR Rate Group	**FY15**	**FY16**	**FY17**	**FY18**	**FY19**	**FY20**
Academic	34.0%	35.0%	35.0%	36.0%	37.0%	37.0%
Staff	42.1%	43.0%	43.0%	44.0%	45.0%	46.0%
Limited	17.5%	18.0%	18.0%	18.0%	19.0%	19.0%
Students (Graduate and Undergraduate)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Notes:

- Approved rates have been reviewed and approved by the Department of Health and Human Services for use by all fund sources for FY14-15. These rates will be applied to gross earnings to generate benefit costs posted to the general ledger.
- Rates beyond June 30, 2015 are estimates and are provided for planning purposes only. Future benefits rates are subject to review and approval by the Department of Health and Human Services on an annual or bi-annual basis.
- Rate changes reflect anticipated increases and decreases in benefit costs, including health care and retirement contributions.
- “Limited” includes Postdocs, Faculty Summer Salary, BYN payments and appointments with BELI code 2, 3 or 4.

Graduate student fees and tuition are considered fringe benefits in budgets to comply with campus cost accounting practices. Under Modified Direct Total Cost, no indirect cost is applied. Current fee amount for FY 14-15 is $8062.75 per semester and will increase estimated 10% annually based on the last 5 year average of fee increases.

Travel Cost. $1,000 ($125/trip, 2 trips per year) is requested for travel from UC Berkeley Sacramento to meet with ARB and project stakeholders.

Publication. $600 is requested for publication of policy analysis and recommendations.

Materials and Supplies. $2,000 is requested for laptop computer to gather data and run model stimulation of F-gas emission scenarios.

Mail, Phone, Fax. $950 ($95/month for 10 months) is requested for web conference services to interface with energy policy experts and ARB.

Analyses. $1,000 is requested for Long-range Energy Alternatives Planning system (LEAP) software license for energy policy analysis and climate change mitigation assessment.

The General, Automobile, and Employment Liability (GAEL) charge was instituted in 1998 to fund the campus's share of expenses associated with claims and lawsuits defended by the University. For Fiscal Year 2014-2015, the GAEL charge is 90 cents per $100 of payroll. This applies to all funds, including gifts and grants, with the exception of direct federal contracts, grants, and flow-throughs. GAEL is considered miscellaneous in budgets per campus accounting practices.

Indirect Cost Base, or Modified Total Direct Costs, consisting of all salaries and wages, fringe benefits, materials, supplies, services, travel and subgrants and subcontracts up to first $25,000 of each subgrant or subcontract (regardless of the period covered by the subgrant or subcontract). Modified total direct costs shall exclude equipment, capital expenditures, charges for patient care, student tuition remission, rental costs of off-site facilities, scholarships, and fellowships as well as the portion of each subgrant and subcontract in excess of $25,000.

9. Curricula Vitae of Key Scientific Personnel

Daniel M. Kammen

Class of 1935 Distinguished Professor of Energy, University of California, Berkeley

(a) Professional Preparation

Cornell University	Physics (cum laude)	A.B.	1984
Harvard University	Physics	M. A.	1986
Harvard University	Physics	Ph.D.	1988
California Institute of Technology	Computational Neuroscience	/ Postdoctoral	1988 - 1991
Harvard University	Energy & Risk Analysis / Postdoctoral		1991 - 1993

(b) Appointments

2012 -	US Department of State, Lead Scholar, Fulbright NEXUS Program
2010 - 2011	Chief Technical Specialist for Renewable Energy and Energy Efficiency, World Bank
2010 -	Senior Energy Fellow, U. S. Department of State (for Energy Cooperation in the Americas)
2008 -	Director, Transportation Sustainability Research Center (TSRC), Institute of Transportation Studies, University of California, Berkeley
2007 -	Editor-in-Chief, *Environmental Research Letters*
2007 - 2008	Award Co-Author and Member Executive Committee, Energy Biosciences Institute (UCB/LBL/UIUC); $500 million biofuels institute funded by BP
2005 - 2009	Co-Director, Berkeley Institute of the Environment
2004 -	Class of 1935 Distinguished Professor of Energy (Chair)
2001 -	Professor of Public Policy in the Goldman School of Public Policy, UC Berkeley
2001 -	Professor in the Energy and Resources Group, University of California, Berkeley
2001 -	Professor of Nuclear Engineering, University of California, Berkeley
1998 - 2001	Associate Professor in the Energy and Resources Group (ERG), UC Berkeley
1997 - 1999	Chair, Science, Technology & Environmental Policy Program (STEP), Woodrow Wilson School of Public and International Affairs, Princeton University
1997 - 1999	Class of 1934 Preceptor, Woodrow Wilson School, Princeton University
1993 - 1999	Assistant Professor of Public and International Affairs, Woodrow Wilson School of Public and International Affairs, Princeton University
1993 - 1999	Research Faculty, Center for Energy and Environmental Studies, School of Engineering and Applied Science, Princeton University
1993 -	Permanent Fellow, African Academy of Sciences

(c) Products (five relevant papers, & five other examples**, from 300+ publications total)**

underline: doctoral advisee of Kammen

1. Jones, C. M. and Kammen, D. M. (2014) "Spatial distribution of U.S. carbon footprints reveals suburbanization offsets benefits of population density", *Environmental Science and Technology*, ***48*** **(2)**, 895 – 902.
2. Mileva, A., Nelson, J. H., Johnston, J., and Kammen, D. M. (2013) "SunShot Solar Power Reduces Costs and Uncertainty in Future Low-Carbon Electricity Systems," *Environmental Science & Technology*, ***47*** **(16)**, 9053 – 9060.
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4. Wei M, Patadia S. and **Kammen DM** (2010) "Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the U. S.?" *Energy Policy*, **38**, 919 - 931.
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10. Margolis, R and **Kammen, DM** (1999) "Underinvestment: The energy technology and R&D policy challenge", *Science,* **285**, 690 – 692.

(d) Synergistic Activities

1. Lead Author and Coordinating Lead Author, (Second and Third Assessment Reports, Special Reports on Technology Transfer and Special Report on Renewable Energy), Inter-governmental Panel on Climate Change, which shared the 2007 Nobel Peace Prize (IPCC)
2. Host and Technology Judge, *Ecopolis*, Award Winning five part Discovery Channel Television Series on Clean Energy Technology Innovation and Dissemination. **URL science.discovery.com/video-topics/gadgets-and-tech/ecopolis.htm**
3. Editor-in-Chief, *Environmental Research Letters*, open access interdisciplinary journal (ISI rating > 3.6) founded in 2007, with over 60,000 downloads/month. URL **erl.iop.org**
4. Author of Energy Bioscience Institute Proposal: $500 million, 10 year biofuels institute: joint between UC Berkeley, Lawrence Berkeley National Laboratory & University of Illinois. URL **http://www.energybiosciencesinstitute.org**
5. Co-inventor/developer of Property Assessed Clean Energy (PACE) Financing Model, and Co-Developer of the Low Carbon Fuel Standard; policies adopted in many municipalities.

(e) Collaborations and Other Affiliations

(e.1) Collaborators and Co-editors

Myles Allen University of Oxford, UK; **Maohong Fan** University of Wyoming, USA; **Peter H Gleick** The Pacific Institute, Oakland, USA; **José Goldemberg** Universidade de São Paulo, Brazil; **Giles Harrison** University of Reading, UK; **Tracey Holloway** University of Wisconsin-Madison, USA; **Klaus Keller** Pennsylvania State University, USA; **Jakob Mann** Technical University of Denmark, Denmark; **Brian O'Neill** National Center for Atmospheric Research (NCAR), Boulder, USA; **Stefan Rahmstorf** Potsdam University, Germany; **Katherine Richardson**, University of Copenhagen, Denmark.

(e.2) Graduate and Postdoctoral Advisors (of DM Kammen)

John Daugman	Department of Neuroscience, Oxford University	Doctoral Advisor
Christof Koch	Division of Biology, California Inst. of Technology	Post-doctoral Advisor
Richard Wilson	Department of Physics, Harvard University	Post-doctoral Advisor

(e.3) Thesis advisor and post-doctoral advisees (of DM Kammen), with their current post

Doctoral graduates in the past five years (38 PhD graduates total): 2012 - Christian Casillas (Ind. Scholar); **Kevin Fingerman** (Asst. Prof. Humboldt State U.); 2011 - **Zachary Norwood** (Lecturer, U. of Götborg); **Anand Gopal** (Lawrence Berkeley National Laboratory); **Derek Lemoine** Asst. Prof., U of Arizona); 2009 – **Charles Kirubi** (Asst. Prof., Kenyatta U.; **Renee Kuriyan** (Intel); **Cyrus Wadia** (White House, OSTP); 2008 - **Daniel Prull** (Prull Enterprises); 2008 – **Matthias Fripp** (Asst. Prof., U. of Hawaii); **Kamal Kapadia** (Lecturer, U. of Hawaii).