

August 2, 2012

## PROPOSAL FOR A RENEWABLE FUELS RESEARCH CENTER

*A white paper submitted to the California Energy Commission*

Submitted by the Sustainable California Study Group at Cal Poly SLO

*Contact:*

William Ahlgren

Electrical Engineering Department

California Polytechnic State University

San Luis Obispo, CA 93407-0355

Tel: (805)756-2309

Email: wahlgren@calpoly.edu

**Proposal to the CEC** The Renewable Fuels Research Center (RFRC)<sup>1</sup> requests seed funding of \$2M each year for five years to begin operations. During the five year incubation period the RFRC will seek other support, both public and private, to grow and sustain operations in future. The RFRC will serve a network of members from a range of academic, commercial, government, and non-government organizations (NGOs). The RFRC will be hosted in the California Polytechnic State University at San Luis Obispo (CPSLO).

**Summary** The RFRC will create an energy transition roadmap and facilitate its implementation. The goal is to replace fossil with renewable (and perhaps nuclear) energy sources, with reduction of GHG emissions by an order of magnitude within decades and achieving zero-net-carbon early in the second half of the century. This will be achieved by building an energy system based on three energy carriers:<sup>2</sup> electric power and two liquid renewable fuels, one nitrogen-based (e.g. ammonia) and one carbon-based (e.g. methanol). The transition requires coordinated technology and business development plans. To meet this need, the RFRC will promote both technological and institutional innovation.

**RFRC fills a gap** Current energy policy supports research that emphasizes natural gas (NG; represented by methane, MeH) as both source and carrier, with hydrogen (H<sub>2</sub>) as a preferred future energy carrier. Much emphasis is placed on the *gaseous* fuels MeH and H<sub>2</sub>; *liquid* fuels receive less attention. Yet, liquid fuels are needed to compete with petroleum-derived fuels. For this reason considerable attention is given to the production of liquid fuels by bioconversion of solar energy. Bioconversion is also assumed to be the future source for zero-net-carbon MeH to replace NG. Bioconversion, however, may not be the most efficient or economic way to produce renewable fuels. Emphasis on gaseous fuels and biofuels leaves a gap in current energy research and a correspondingly limited range of energy policy options. The RFRC seeks to fill this gap in energy research and thus widen the range of options available to energy policy-makers.

**Liquid is key** The RFRC will focus on *liquid* fuels that are renewable, but not necessarily bio-derived. The RFRC will put emphasis on ammonia (NH<sub>3</sub>) and methanol (MeOH) as the simplest liquid energy carriers. These fuels can be produced using *any* energy source,

---

<sup>1</sup> A nomenclature list defining all acronyms used is appended as the last page of this document.

<sup>2</sup> Energy carriers are also known as energy *vectors*.

including (but not limited to) bioconversion of solar energy.  $H_2$  and NG have many desirable characteristics but suffer from the intrinsic problem that they are *gases*. The legacy infrastructure, built for petroleum-derived liquid fuels, cannot readily accommodate these gaseous fuels.<sup>3</sup> Liquid fuels such as  $NH_3$  and MeOH, by contrast, can be accommodated in the legacy infrastructure with relatively low-cost modification. The benefits of  $H_2$  can be achieved with  $NH_3$  and MeOH without prohibitive infrastructure costs; thus this *dual-fuel* path to zero net carbon can succeed where  $H_2$ , after a half-century of effort, has made little progress.

$NH_3$  can be thought of as a liquid form of  $H_2$ , and MeOH as a liquid form of NG. Both  $NH_3$  and MeOH can be efficiently produced from NG, thus offering a gas-to-liquid (GTL) path for the monetization of stranded gas fields. Both can also be produced from renewable sources including wind and solar as well as nuclear sources. They are source-neutral liquid renewable fuels that can compete with and displace petroleum-derived fuels.  $NH_3$  derived from NG with carbon capture sequestration and sale (CCSS) offers a path to significant near-term reduction in greenhouse gas (GHG) emissions.

**Alternative to biofuels** After decades of study and development, the potential of biofuels to meet the world's energy needs remains uncertain. Corn ethanol (EtOH), the most widely used biofuel in the U.S. today, is widely conceded to be unsustainable. Other food crops such as soy beans can be used to make other fuels ("biodiesel"); this path also is unsustainable. Sugarcane EtOH, used extensively in Brazil, is likewise believed by many experts to be unsustainable. There is significant controversy around cellulosic EtOH, but there is the likelihood that it too is unsustainable.<sup>4</sup> Algae cultivation especially for dual-use (e.g. sewage treatment and fuel production) is perhaps the least controversial bio-conversion route; but efficiency and economics are uncertain for it too. It is prudent therefore to develop an energy transition plan that is consistent with bio-conversion of solar energy but not dependent on it. The RFRC will develop and implement such a plan.

**Approach** The RFRC will develop an energy transition plan based on the dual-fuel strategy,<sup>5</sup> summarized in this section. The transition from fossil to renewable energy will be accomplished in two steps: first, replace petroleum with NG; second, replace NG with renewable sources (primarily wind and solar). The key to Step 1 is GTL conversion, enabling the NG *source* converted to liquid *fuels* (energy carriers) to compete with petroleum in all energy sectors. We select  $NH_3$  and MeOH as the primary liquid fuels to be

---

<sup>3</sup> Natural gas is widely used in the legacy infrastructure but remains marginally competitive with petroleum due to limitations on transport and storage. Natural gas is competitive when it can be transported overland by pipeline from source to end-use; else it is "stranded." Stranded natural gas fields can be monetized by GTL conversion; production of ammonia and methanol from natural gas is such a process. Even gas resources that are not stranded can be more effectively utilized through efficient GTL conversion.

<sup>4</sup> Cellulosic ethanol is derived from low-starch-and-sugar fuel crops (e.g. switchgrass) or from field and forest residue (e.g. wood chips, corn husks, and the like). A fraction of food and timber crop residue can be diverted to energy production (e.g. corn cobs can be removed while stover is left on the fields; wood chips generated during milling of lumber can be converted to fuel while the branches of felled trees are left in the forest). Diversion of more than a small fraction of agricultural "waste," however, results in unsustainable soil depletion. This small fraction is a useful contribution, but by itself not nearly sufficient to displace petroleum.

<sup>5</sup> W. L. Ahlgren, "The Dual-Fuel Strategy: An Energy Transition Plan," *Proc. IEEE* **100**: 0000-0000 (Nov. 2012); pre-print available at IEEE Xplore (<http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6235977>) or from the author ([wahlgren@calpoly.edu](mailto:wahlgren@calpoly.edu)).

derived from NG. They have particular advantages in the near term for GHG reduction; they provide an easy path to Step 2 (in which the *same* fuels will be produced from renewable sources); and they are sufficiently compatible with existing infrastructure to enable relatively low-cost and rapid deployment.  $\text{NH}_3$  and MeOH is a dual-fuel pair. They are complementary, each with strength to compensate the other's weakness:  $\text{NH}_3$  is carbon-free but has high relative toxicity; MeOH has low relative toxicity<sup>6</sup> but contains carbon. Together, using each in its proper domain, this dual-fuel pair provides the best solution for the transition from fossil to renewable fuels.  $\text{NH}_3$  will be used whenever professional fuel handlers can be employed; MeOH will be used when non-professionals must handle fuel; a secondary fuel derived from MeOH will be used when high energy density is mandatory.

Step 1 enables Step 2 by creating a consumer market for  $\text{NH}_3$  and MeOH as fuel. Because NG is a low-cost resource,  $\text{NH}_3$  and MeOH derived from NG will have a strong price-driven competitive advantage against petroleum-derived fuels. This will enable them to rapidly displace petroleum in the market. The growing market for these fuels will then drive the technology development required to produce them from renewable sources. Unlike petroleum-derived fuels (gasoline, kerosene and diesel fuel),  $\text{NH}_3$  and MeOH are *simple* energy carriers that *can* be efficiently produced from renewable sources. This is a necessary condition for the requisite technology development in Step 2. Technology development will occur after Step 1 has created the market to drive it.

Step 1 is the transition from petroleum to NG as *source* with  $\text{NH}_3$  and MeOH as *carriers*. During this first step it will be possible to concentrate  $\text{CO}_2$  generation in a few large sources: ultra-mega  $\text{NH}_3$  and MeOH production plants located near the gas fields. This concentration will enable CCSS. In this scenario, significant GHG reduction can occur during Step 1. This is illustrated in the figure below, which shows how the average global fuel carbon intensity might vary as renewable fuels are introduced.

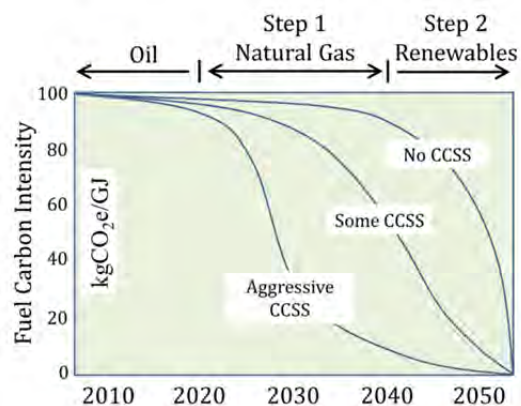


Fig. 1: Global energy transition scenarios.

<sup>6</sup> “Relative toxicity” means relative to gasoline, selected as a familiar benchmark liquid fuel. MeOH is similar to (actually less toxic than) gasoline; both can be safely handled with only modest precautions. NIOSH assigns an IDLH value of 6000 ppm to methanol and 500 ppm to toluene, one of the major components of most gasoline blends. IDLH is a higher-is-better figure of merit; by this measure gasoline that is one-fourth toluene has an effective IDLH of 2000 ppm, three times “more toxic” than MeOH. Gasoline, moreover, also contains substances such as benzene which are carcinogenic, a health hazard not assessed by IDLH. Note also that completely non-toxic fuel is apparently not desired; e.g. fuel EtOH is “de-natured” by adding poison!

In all scenarios, the fuel carbon intensity falls to zero when all fuels are produced using renewable sources with only air and water as feedstock, as shown in Fig. 2.

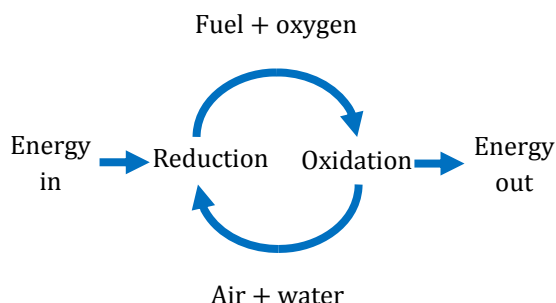
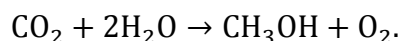
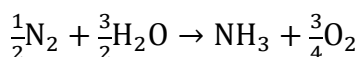
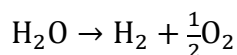


Fig. 2: Renewable fuel cycle.

Air consists primarily of nitrogen, oxygen, argon, and carbon dioxide. Nitrogen and carbon dioxide from air, together with water, are the substances available to make renewable fuels. The leading candidates for renewable fuels are thus  $H_2$ ,  $NH_3$ , and  $MeOH$ :



$H_2$  is rejected because it is a gas, too difficult to use in the legacy infrastructure.  $NH_3$  is a nitrogen-based liquid fuel and is easier to derive from air and water than is  $MeOH$ , which is carbon-based. This is because nitrogen is 2000 times more plentiful in air than carbon dioxide. Nevertheless, the natural process of photosynthesis<sup>7</sup> demonstrates that it is feasible to produce renewable fuels from the carbon dioxide in air. Because it is nitrogen-based,  $NH_3$  will be the least expensive fuel that can be derived from air and water plus renewable energy.  $MeOH$ , because it is carbon-based, will be more costly; but there are applications in which the higher cost is justified due to ease of handling. Most highway transportation applications fall into this category.  $MeOH$  can be converted to dimethyl ether (DME) at low cost and with high efficiency, thus we regard these two fuels as interchangeable. DME may be preferred, for example, in compression ignition (CI) engines,

---

<sup>7</sup> Natural photosynthesis produces carbohydrates from air, water, and solar energy:  $CO_2 + H_2O \rightarrow (HCOH) + O_2$ , where (HCOH) represents a carbohydrate monomer. Carbohydrates are excellent building materials for self-assembling, self-replicating organisms; but they are not good fuels. Artificial photosynthesis of methanol or ammonia directly from solar energy is a worthy research goal. Equally worthy is the bioengineering of organisms that implement such a photosynthetic mechanism to directly produce useful fuels. Yet another worthy goal is the engineering of systems incorporating organisms that not only produce fuel but also serve another useful function, such as waste treatment. The RFRC will include these in its research agenda. Less promising biofuel pathways are those which use natural photosynthesis to first produce complex carbohydrates (lignocellulosic biomass and the like) which must then be converted back to simple substances like alcohols for use as fuel. This is an inherently inefficient process; inefficient solar conversion can, however, still make sense if it is sufficiently low cost. Research on these inefficient bioconversion routes to fuel production is adequately covered by other organizations, and will not be addressed by the RFRC.

and as a replacement for NG and propane in habitation applications such as space and water heating and cooking. Some applications, for example long-haul air-transport, require high-energy density that can only be delivered by a carbon-rich fuel such as dodecane (DDC,  $C_{12}H_{26}$ , the primary reference substance for kerosene or jet fuel). Such fuels can be produced at additional cost from air-derived MeOH using established technology such as the Mobil MTG (methanol-to-gasoline) process. The higher cost to produce these fuels will again be justified by the particular advantage they provide (high-energy density); but only for those few applications where this is really an advantage. An approximate division of renewable liquid fuels among  $NH_3$ , MeOH (including DME), and DDC is shown in Fig. 3.

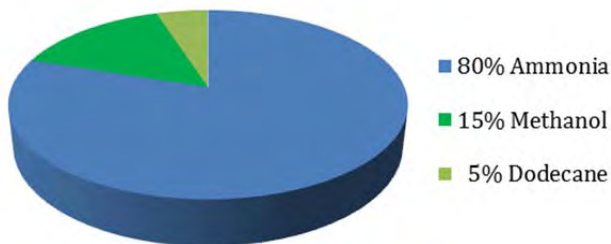


Fig. 3: Estimated shares of the total fuel market. Ammonia dominates, methanol is important, dodecane is small but essential.

This figure is based on analysis of U.S. Energy Information Agency (EIA) data for 2009. All those fuel uses that can employ professional fuel handlers and do not require high energy density are assigned to  $NH_3$ ; those that require non-professional fuel handlers but can still tolerate low energy density are assigned to MeOH; those that require high energy density are assigned to DDC. It is assumed that in transportation applications cost trumps range except for military and long-haul commercial aviation applications. We assume highway drivers are willing to refuel twice as often in exchange for travelling to their destination at half the cost. Vehicles which today can travel from Los Angeles to San Francisco on a single tank of fuel will instead have to stop in San Luis Obispo to refuel; but the trip will cost the driver half as much. We think this is a trade most drivers will make. Further, it is possible to recover range capability by making gas tanks larger and engines more efficient; the trade-offs involved are topics for the RFRC's research agenda.

$NH_3$  and MeOH (and its derivatives) when produced from air, water, and renewable energy are zero-net-carbon (carbon neutral) fuels. Prior to their advent, significant GHG reductions might be possible if the  $CO_2$  generated during  $NH_3$  production from fossil sources is kept out of the atmosphere by CCSS. The extra *S* in this acronym emphasizes that *sale* of valuable products incorporating carbon can partly offset the cost of capture. The feasibility of doing so is enhanced by producing  $NH_3$  in a small number of very large plants, thus centralizing the capture operation. Fig. 4 illustrates this strategy as it applies to electric power generation, for example. It is easier to capture  $CO_2$  at 5 gas fields than at 390 power plants. If CCSS were implemented at a small number of very large NG-to- $NH_3$  conversion plants located near the 5 gas fields shown in Fig. 4, a very significant fraction of the GHG emissions associated with electric power generation in California would be eliminated.



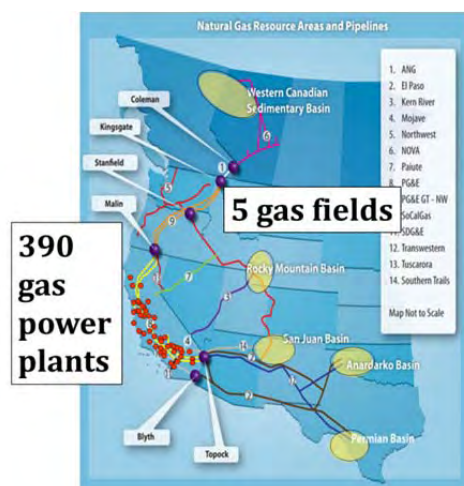


Fig. 4: Concentration of CO<sub>2</sub> generation at the gas fields can enable low-FCI NH<sub>3</sub> through carbon capture sequestration and sale.

By fuel carbon intensity (FCI) we mean the life-cycle assessment of the *process chain* by which the fuel is produced and used. Using AB 118 language,<sup>8</sup> this process chain includes (1) feedstock production, extraction, transport, and storage; (2) fuel production, distribution, transport, and storage; and (3) vehicle (or other end-use converter) operation, including refueling, combustion, conversion, permeation, and evaporation. The intrinsic fuel carbon intensity (IFCI) is the value if only the carbon contained in the fuel itself is counted; it is 54.9 kgCO<sub>2</sub>/GJ for MeH, 69.0 for MeOH; these may be compared with FCI values of 68 for CNG and 76 for MeOH if both are produced from NG.<sup>9</sup> and IFCI is zero for H<sub>2</sub> and NH<sub>3</sub>. This zero value of IFCI for H<sub>2</sub> and NH<sub>3</sub> is misleading, however, since the near-term low-cost supply of these fuels is from NG. Therefore we define the methane-derived IFCI (mdIFCI) to be the value if the fuel is derived from MeH with all the carbon converted to CO<sub>2</sub>; this is 91.0 kgCO<sub>2</sub>/GJ for H<sub>2</sub> and 104.2 for NH<sub>3</sub>. The mdIFCI gives a rough estimate of the FCI values for carbon-free fuels like H<sub>2</sub> and NH<sub>3</sub> if they are produced from NG with no CCSS. With CCSS, however, the FCI of either H<sub>2</sub> or NH<sub>3</sub> produced from NG can be reduced; with very efficient CCSS it can approach zero.<sup>10</sup>

<sup>8</sup> California Assembly Bill No. 118 (Nunez, 2007), Alternative Fuels and Vehicle Technologies: Funding Programs.

<sup>9</sup> FCI and IFCI are calculated based on the lower heating value (LHV) of the fuel. The IFCI of methanol is lower than that of methane because inserting oxygen lowers the LHV. FCI is specified in units of kgCO<sub>2</sub>e/GJ; the “e” is omitted in the units of IFCI. The “e” stands for “equivalent” and signifies that additional GHGs, primarily MeH and N<sub>2</sub>O, are also accounted for in the LCA. It reflects the fact that FCI is characteristic of a *process chain* and not a *substance*. IFCI by contrast is characteristic of a particular fuel substance only; it is not derived from an LCA. IFCI focuses on a single link in a long process chain: the oxidation of the fuel substance itself. It cannot account for either emission to or extraction from the atmosphere of GHGs extraneous to that single link.

<sup>10</sup> When the full life-cycle is taken into account, some level of GHG emissions will be associated with any fuel. We aim for this level to be low, not zero. At the combustion step of the process chain, some NO and N<sub>2</sub>O and other nitrogen oxides will be produced when air is used as oxidizer, no matter what the fuel is. This is because the reaction of N<sub>2</sub> and O<sub>2</sub> to produce NO (a precursor for N<sub>2</sub>O and other nitrogen oxides) is favored at high temperature. Counter-intuitively, emission of nitrogen oxides for NH<sub>3</sub> combustion can potentially be *less* than for H<sub>2</sub>; NH<sub>3</sub> is today injected into combustors or used in post-combustion treatment processes to suppress NOx emission.

The FCI for any fuel production and use process must be determined by detailed life-cycle analysis (LCA). Prior to full LCA, however, the IFCI and mdIFCI values can be used to estimate what might be achievable. Petroleum-derived fuels have IFCI values in the range 65 kgCO<sub>2</sub>/GJ for paraffins to 85 for aromatics; take 75 as an average value.<sup>11</sup> The IFCI of MeH is 54.9 kgCO<sub>2</sub>/GJ. Thus if the global economy were entirely petroleum-based today and changed to entirely NG-based tomorrow, a 27% reduction in CO<sub>2</sub> emissions would result. If instead 80% of the NG (assumed to be pure MeH) is converted to NH<sub>3</sub> with CCSS, and the remaining 20% is converted to MeOH, then the average global IFCI falls to 13.8 kgCO<sub>2</sub>/GJ; an 81% reduction compared to the current petroleum-based world economy. If partial CCSS is implemented in NH<sub>3</sub> production, capturing (for example) only 70% of the CO<sub>2</sub> generated, then the average IFCI becomes 45 kgCO<sub>2</sub>/GJ, a reduction of 40% compared to business as done now, still quite respectable. These are rough estimates of the relative reduction<sup>12</sup> in GHG emissions that can be feasibly attempted in the near-term (perhaps by 2030). The reductions can be achieved using low-cost NG as the energy source, even without resorting to renewable sources.

Significant near-term GHG reduction during Step 1 is feasible; but even more important is the development of markets for NH<sub>3</sub> and MeOH as fuel. These markets enable Step 2: the transition from NG to renewable sources. When this latter transition is complete, GHG emissions fall to near zero. That includes emissions from MeOH and MeOH-derived fuels which are carbon-neutral when Step 2 is completed, because then the carbon in the fuel is captured from the atmosphere. This ultimate goal can be feasibly achieved in the latter half of the century (perhaps by 2050). This is possible because of the competitive advantage inherent in the dual-fuel strategy.

**Competitive advantage** Competitive advantage for the dual-fuel strategy comes from: (1) legacy compatibility; (2) agile production; and (3) risk mitigation. *Legacy compatibility* means that the existing energy infrastructure can be used with minimal modification. This translates to easy entry to the dual-fuel energy market. Participation in this market requires some initial investment, but the barrier is low because existing physical plant can be used with minimal modification. *Agile production* means that market participants can draw not only on petroleum as a source of energy, but also on coal and gas and eventually on renewable and nuclear sources. Producers can diversify their sources and methods; and if they don't, distributors and customers can turn to other producers who do. *Risk mitigation* is against two major risk categories: petroleum supply and global-warming-related business factors. The dual-fuel strategy provides a hedge against the risk that declining conventional petroleum reserves will lead to erratic supply and price. It is also a hedge against the risk that the reality of global warming will compel government-mandated carbon taxation (or other forms of carbon restriction) in the near future. Such an eventuality, if it transpires, will give dual-fuel producers and consumers an overwhelming advantage over competitors who engage only in business as done now. Despite these

---

<sup>11</sup> For comparison, the CARB-accepted FCI of gasoline is 96 kgCO<sub>2e</sub>/GJ. FCI is usually greater than IFCI, but can be less if the process chain includes a link in which CO<sub>2</sub> is captured from the air; negative FCI is possible if more carbon is removed from the air (and then sequestered in a non-fuel form) than is put back into the fuel.

<sup>12</sup> The relative (percent) reductions are useful estimates; for absolute amounts FCIs are needed. The relative values are good estimates assuming FCIs associated with different fuels are all greater than the corresponding IFCIs by the same amount, say 20%.

advantages economic inertia creates a barrier to change. Economic inertia is caused by positive market feedback; the same positive market feedback can be used to overcome economic inertia and create rapid change.

**Market feedback** Economic inertia results from an economic *vicious cycle*, a form of positive feedback that opposes change. In the case of fuel, the vicious cycle works like this: conversion devices (engines and combustors) that consume alternative fuels are not available, so there is no incentive to produce and distribute alternative fuels; but in the absence of widely available alternative fuels, there is no incentive to develop conversion devices that would consume them. This Catch 22 blocks the adoption of alternative fuels, even if they could be less costly than fossil fuels.

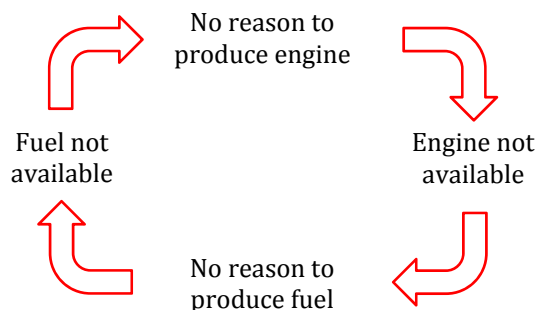


Fig. 5: Feedback prevents change.

To overcome this vicious cycle, we must replace it with a *virtuous cycle*. The same market feedback mechanism that prevents change will promote it after a use-threshold is crossed; feedback accelerates change once it is triggered.

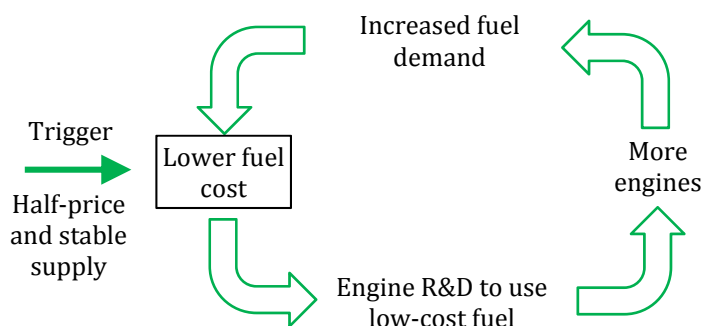


Fig. 6: Feedback promotes change.

The challenge is to identify the path of least resistance to change and focus financial and technological resources there. This path lies through a few niche markets where renewable fuels have lowest barrier to adoption and compelling competitive advantage. Successful development of these *trigger markets* will lead rapidly to global change once a renewable fuel use threshold is reached.

**Trigger markets** The energy transition from fossil to renewable energy sources will be initiated by the availability of liquid renewable fuels, compatible with the legacy



infrastructure, at half the cost per unit energy of competing petroleum-derived liquid fuels and with the guarantee of long-term supply and price stability. Trigger markets are applications in which renewable fuels are best positioned to displace their entrenched fossil competitors. In these applications the competitive advantage of a renewable fuel ( $\text{NH}_3$  or  $\text{MeOH}$ ) is greatest and the barrier to adoption presented by required investment in new infrastructure is lowest. Examples of trigger markets are: (1) road transport local fleets; (2) railway locomotives; (3) marine propulsion; (4) mid-scale energy hubs; (5) base-load electric power. Trigger markets serve to initiate positive feedback in the larger marketplace, creating a virtuous cycle that (once triggered) leads rapidly to market dominance. These five examples of trigger markets are described in more detail next.

*Road transport local fleets* Wide-spread fuel distribution is a daunting problem for  $\text{H}_2$ , and to a lesser extent for NG. By contrast it is relatively easy for  $\text{MeOH}$ , which can be added to existing retail fuel stations with quite modest investment. Still, a significant chicken-and-egg problem remains: vehicles won't become available without stations to serve them, but stations won't become available without first having vehicles to serve. This problem can be solved by re-starting the very successful CEC-sponsored California  $\text{MeOH}$  project of the 1980s and 90s. As then, an initial market opportunity is presented by government and corporate fleets with vehicles used only for local trips. These vehicles can be re-fueled from private depots.  $\text{MeOH}$  can be supplied to these depots in bulk shipments, thus circumventing the distribution problem. This is a particularly attractive target for a near-term large-scale project since the ground-work has already been done. All that is needed is to re-start a program the success of which has already been proven. The California  $\text{MeOH}$  project ended soon after petroleum and gasoline prices declined sharply in about 1987.<sup>13</sup>

---

<sup>13</sup> The  $\text{MeOH}$  program sponsored by the CEC throughout the 1980s was very successful at the local fleet demonstration level. After over a decade of successful technology development and demonstration, in 1990 the program was poised to take the next step: scale-up to achieve state-wide impact. This was to be accomplished by mandating that  $\text{MeOH}$  storage and dispensing capability be incorporated by retail fuel outlets as part of their normal 10-year facilities renewal cycle. This "methanol mandate" would have been implemented by legislation, AB 234 (Leonard, 1987). The bill was opposed by petroleum interests represented by the Western States Petroleum Association (WSPA); it was eventually passed as a study bill only, with emphasis on air quality, thus to be implemented by CARB. At public hearings before CARB in September of 1990, George Babikian of ARCO offered reformulated gasoline (EC-1) as an alternative to  $\text{MeOH}$ . This was sufficient to meet the state's air pollution targets at the time and was thus acceptable to CARB; but it met no energy security goals (not prominent in the 1987-1990 time period due to temporarily low gasoline prices). CARB's authority under the California Clean Air Act (Sher, 1988) does not make energy security a priority; thus the WSPA succeeded in revising the regulatory implementation of AB 234 to avoid the methanol mandate. This effectively ended the CEC's  $\text{MeOH}$  program, which wound down in the early 1990s. It was replaced by a zero emission vehicle (ZEV) mandate with an almost exclusive focus on electric storage batteries and  $\text{H}_2$  fuel cells as the path to low-carbon highway transportation. Two decades later, we now understand the intrinsic limitations of batteries and  $\text{H}_2$ , as well as the full scope of the energy challenge we face. Today we understand that air quality, climate change mitigation, and energy security are inter-related and equally important aspects of a single energy problem, and that liquid renewable fuels are a necessary part of the solution.  $\text{MeOH}$  is the simplest, lowest-cost choice for highway transport. The CEC can now revisit  $\text{MeOH}$  with a view to providing policy options for today's legislators. The ZEV mandate can be replaced with a F3V mandate (see box, following page). Auto companies will support this approach because F3Vs are easier and less costly to implement than battery electric vehicles (BEVs) or  $\text{H}_2$  fuel cell vehicles (FCVs). Further, since petroleum and natural gas investments are often interlocking, presenting  $\text{MeOH}$  as a GTL conversion option for monetizing stranded natural gas can deflect opposition from entrenched petroleum interests.

This project can be re-started now. Its continuing viability will be assured by a strategy to maintain the price of MeOH at half that of gasoline (on an energy basis; one-fourth on a volume or mass basis). This can be done in the current (and future) environment of high petroleum cost and low NG cost. Fueling road vehicles with MeOH enables multiple technology paths to GHG reduction:<sup>14</sup> (1) conversion of existing vehicles; (2) development of advanced ICE-powered MeOH-compatible flex fuel vehicles (FFVs); (3) development of fully flex fuel vehicles (F3Vs, see box below); and (4) ultimately (perhaps), electric vehicles powered by direct MeOH fuel cells (fuel cell vehicles, FCVs).

***Technology evolution from FFV to F3V*** MeOH-powered local fleets can serve as demonstration projects for the development and commercialization of fully flex fuel vehicles (F3Vs). F3Vs are plug-in hybrid-electric vehicles (PHEVs) with on-board engine-generator systems (possibly gas turbines, GTs) capable of accepting any mixture of gasoline and alcohols, up to and including pure MeOH or EtOH. This is not a technologically ambitious goal—it is only a small step beyond a Chevy Volt. All major automobile manufacturers already make flex fuel vehicle (FFV) models powered by conventional ICEs capable of operating on EtOH-gasoline blends ranging from zero to 85% EtOH (E85).<sup>15</sup> Further modification to enable operation on any MeOH-EtOH-gasoline blend up to about 85% alcohol is possible at low cost (on the order of hundreds of dollars per vehicle); indeed this is mandated by proposed federal Open Fuel Standard (OFS) legislation.<sup>16</sup> In the near term, MeOH-compatible FFVs can be supplied by auto makers in quantity and at low marginal cost. F3Vs are advanced vehicles representing the culmination of the trend toward fuel flexibility. F3Vs offer superior flexibility in choice of energy carrier: electricity or a wide range of fuels; fuels which can in turn be produced from a wide range of energy sources, including (but not limited to) renewable sources such as wind and solar. All the components required to make high-performance low-cost F3Vs are proven technology elements already in commercial production; all that is needed is their integration into a system. F3Vs offer a comprehensive near-term solution to the energy problem in the highway transport sector. This solution addresses all three major issues: air quality, climate change mitigation,<sup>17</sup> and energy security. Further, it does so with existing technology that can be deployed in the near term and with relatively low infrastructure investment. MeOH-powered local fleets are the test bed needed to realize the potential of F3Vs.

---

<sup>14</sup> GHG reduction comes not from fuel substitution *per se*, but by building an energy process chain that enables renewable sources to provide the energy carried by the fuel. The FCI of gasoline produced from petroleum will always be what it is now: about 96 kgCO<sub>2</sub>e/GJ. By contrast the FCI of methanol can decrease toward zero over time as more and more renewable sources are used to produce it. The IFCI of MeOH is 69 kgCO<sub>2</sub>e/GJ. MeOH produced from NG has an FCI of about 76 kgCO<sub>2</sub>e/GJ. MeOH produced using renewable sources (hydroelectric, wind, and some biomass sources for example) can have FCI on the order of 10 kgCO<sub>2</sub>e/GJ.

<sup>15</sup> Models certified for sale and operation in California are listed by CARB at [www.driveclean.ca.gov](http://www.driveclean.ca.gov).

<sup>16</sup> An advocacy Web site providing information on the content and status of proposed OFS legislation can be found at [www.openfuelstandard.org](http://www.openfuelstandard.org).

<sup>17</sup> Life-cycle analysis teaches that there is no such thing as a ZEV. Instead, there are low-carbon *systems*: process chains from energy source to end use via one or more energy carriers. In this context, F3Vs can do more to implement a low-carbon fuel standard than can so-called ZEVs.

*Railway locomotives* Engines powering trains with all kinds of cargoes can be relatively easily converted to use  $\text{NH}_3$  as fuel because they can bring their fuel with them; as many separate fuel cars as are needed can accompany the locomotive. Rail transport does not need to rely on an extensive re-fueling infrastructure; fuel depots at just a few nodes in the rail network suffice.  $\text{NH}_3$  can be used as fuel since professional fuel-handlers are employed.  $\text{NH}_3$  is already carried in railway cars, so is familiar.<sup>18</sup> Industry and regulatory agency cooperation is of course imperative. Interest on the part of regulatory officials in innovation and in promoting alternative fuels is crucial; here government has an important role to play. Currently rail locomotives are powered by diesel fuel, with which  $\text{NH}_3$  is already price-competitive, just as it is with CNG.

*Marine propulsion* Most contemporary shipping relies on low-grade marine bunker fuel-oil that combines high energy density with low cost; it would be hard to compete with these fuels. Their use, however, must be phased out in the coming decade to meet new emission constraints required for environmental protection of heavily used sea lanes. A frequently discussed replacement is CNG; but compression of NG is not as efficient from a life-cycle perspective as conversion to liquid MeOH or  $\text{NH}_3$ . Marine propulsion is therefore a near-term opportunity to develop a market for MeOH and  $\text{NH}_3$  as fuels. It is a desirable trigger market because the logistics problem is minimal; fuel storage and distribution is needed at only a small number of ports world-wide. Shipping employs professional fuel handlers and this in the long term is a suitable application for  $\text{NH}_3$ . Currently, however, International Maritime Organization (IMO) rules ban the use of  $\text{NH}_3$  on most ships, therefore MeOH must be used until these regulations can be changed. Meanwhile,  $\text{NH}_3$  tankers can be used as first development platforms for future  $\text{NH}_3$ -powered shipping of all kinds.

*Energy hubs* The 21<sup>st</sup> century global energy system will be organized around energy hubs. Energy hubs are nodes in an energy network trading both electric power and renewable fuels. They are an evolutionary development of the current energy system in which both electric power and NG are distributed, often by the same company. Energy hubs are decentralized (distributed, in power engineering parlance) versions of the current energy supply system. They are designed to take advantage of the overall system efficiency gains that can be achieved through distributed generation in mid-scale (MW-size) power plants designed for tri-generation (combined cooling, heat and power) in connection with district cooling and heating systems. The core of each energy hub will be energy conversion systems such as hybrid solid oxide fuel cell-gas turbine (SOFC-GT) fuel-to-electric-power converters; and solid oxide electrolysis cell (SOEC) electric-power-to-fuel converters. A near-term market exists for energy hubs on the order of 10-100 MW in size, serving communities of 2,000-20,000 people; we call these mid-scale energy hubs. Certain communities are particularly well-placed as potential customers; these include farming communities located near existing  $\text{NH}_3$  terminals and island communities easy to reach by sea and without sufficient local energy resources. This small near-term market has

---

<sup>18</sup> Transport of  $\text{NH}_3$  in railway tankers is widely practiced, yet remains controversial. This has to do mainly with legal issues: Who assumes the risk associated with accidental spills? Is that party adequately compensated for the risk they assume? Do they need to be shielded from lawsuits arising from circumstances beyond their control? These are not technology issues, but policy questions that must be resolved through legislation.

unlimited growth potential as the entire global energy system converts over the course of the 21<sup>st</sup> century to the distributed generation paradigm. The development of this technology will be a particular focus of the RFRC.

*Base-load electric power* NG-fired boilers generating steam for base-load electric power production are a target market with the potential for very significant GHG emission reduction in the near term. Industrial process heat (e.g. Portland cement manufacture) is a similar alternative target application. NH<sub>3</sub> is easier and safer to transport and store than is NG, especially if transport is over water. There are three NH<sub>3</sub> terminals on the West Coast, two of them in California (Stockton and West Sacramento); there are no LNG terminals in California.<sup>19</sup> Over land, NH<sub>3</sub> can be transported in pipelines more efficiently than NG. Power transmission by NH<sub>3</sub>-pipeline is a low visual and environmental impact alternative to power transport by high-voltage electric transmission lines. NH<sub>3</sub> has near-zero point-of-use emissions. These advantages will drive conversion from NG to NH<sub>3</sub>. Boilers and furnaces can be readily converted as soon as low-NO<sub>x</sub> burners are commercially available, and no other part of the plant needs to change. Plants located near existing NH<sub>3</sub> pipelines, or near seaports with terminals capable of handling NH<sub>3</sub> tankers, are natural choices since relatively short and inexpensive pipeline construction will be able to supply them. Power plants or other industrial plants meeting this geographic criterion and in need of boiler or furnace upgrade or replacement are prime candidates for early adoption.

**Scope of the RFRC** Triggering the transition from fossil to renewable energy requires both technology and institutional development. The scope of the RFRC includes both.

*Technology development* The RFRC will develop technology around liquid renewable fuels based on NH<sub>3</sub> and MeOH and including derivatives such as DME and higher alcohols or alkanes such as DDC required for special applications (e.g. long-haul aviation). We will develop the required technology, including both near-term *use* (engines, combustors, fuel cells, etc.) and long-term *production* (solar and wind energy conversion to the liquid renewable fuels NH<sub>3</sub> and MeOH). Near-term use of NH<sub>3</sub> as fuel requires that it be burned in combustion engines. Very low-emission combustion of NH<sub>3</sub> is theoretically possible but has not yet been demonstrated. Doing so is a high priority as it opens important near-term trigger markets to NH<sub>3</sub> fuel: train and ship propulsion as well as stationary electric power generation. In the longer term zero-emission electrochemical engines (fuel cells) will replace many combustion-powered converters. High-efficiency inter-conversion between electric power and renewable fuels (i.e. both fuel cells and electrolyzers) is therefore another key RFRC research theme. This is *disruptive technology*: it is challenging, but if achieved it will radically alter the techno-economic landscape and enable a rapid solution of the global energy puzzle. It will definitively solve the energy storage and transportation problems associated with stochastic and remote renewable energy sources.

Electrochemical conversion is one path from wind and solar energy to renewable fuel; another is direct conversion of solar energy to fuel by a photosynthesis process, which can be artificial (e.g. photo-electrochemical) or biological (e.g. algae). The RFRC will develop biofuel technology as appropriate, investigating promising paths not taken by other research organizations in this already well-studied field. The main thrust of the RFRC,

---

<sup>19</sup> The only LNG terminal on the West Coast is the Costa Azul facility in Baja California, Mexico. It was situated there because public concern over the hazards of LNG precluded its location in California.

however, will be to address an important unmet need: the development of energy conversion devices (both combustion and electrochemical) for  $\text{NH}_3$  and MeOH with the specific goal of opening trigger markets for these fuels. This important technology goal is currently not addressed by any research institution; the RFRC will fill this gap. A list of some of the technology development tasks that might be undertaken by the RFRC is given in an appendix. This list is by way of example only; the RFRC research agenda will be guided by a business and technology roadmap to be developed by a consortium that includes leading commercial stake-holders.

***Institutional development*** The RFRC will be a seed organization not only for technology development, but also for the development of institutions. Two institutions that are needed are (1) a pre-competitive research consortium; and (2) a market facilitator. The pre-competitive research consortium will be a public-private partnership modeled on such organizations as EPRI, SEMATECH, and USCAR. This organization will create and maintain a business and technology development roadmap to guide the transition from fossil to renewable fuels, and will distribute funds to research organizations which will carry out the necessary technology development. The market facilitator may be called the Dual-Fuel Exchange (DFX). It is to be a meta-market that will rely on existing commodities exchanges to bring together energy consumers, suppliers, and servicers for mutual benefit based on the inherent competitive advantage of  $\text{NH}_3$  and MeOH fuels. To participate in the DFX some investment is required; but the investment barrier is relatively low because  $\text{NH}_3$  and MeOH are liquid fuels with well-established technology already in place. The benefits of participation are high because these fuels can be supplied at low and stable cost compared to their petroleum-derived competitors. The competitive advantage inherent in the dual-fuel strategy will drive growth of the DFX.

**Tri-state alliance** The RFRC will be the California member of a tri-state alliance of academic research centers dedicated to fulfilling our shared vision. Other alliance members are the Iowa Energy Center and the Colorado School of Mines. The activities of these three member organizations will be closely coordinated to achieve maximum near-term impact. We will leverage the resources of the states of Iowa, Colorado, and California with federal and private support, all directed toward a common goal following a consensus technology and business development roadmap. The tri-state alliance derives from an annual meeting, the  $\text{NH}_3$  Fuel Conference, sponsored by the Iowa Energy Center and the  $\text{NH}_3$  Fuel Association. This annual meeting will continue to be the primary venue for coordination of research activities and mutual support.

Additional RFRC affiliates will be businesses as well as government organizations and NGOs with interest in promoting efforts to help avert global climate catastrophe. Many of these will be located in the State of California. Among potential affiliates are the  $\text{NH}_3$  Fuel Association, the William J. Clinton Foundation, Lawrence Livermore National Laboratory (Livermore, CA); Argonne National Laboratory; Space Propulsion Group (Mountain View, CA); and Carbon Recycling International. We anticipate that when an initial source of financial support is found our list of affiliates will grow rapidly.

**Conclusion** The RFRC will fill a void in current energy research and development efforts. Much attention is currently given to H<sub>2</sub> and NG, but these gaseous fuels cannot compete with petroleum-derived fossil fuels, which are liquids. NH<sub>3</sub> can be viewed as a liquid form of H<sub>2</sub>, and MeOH as a liquid form of NG. Both NH<sub>3</sub> and MeOH are currently produced commercially in large quantities, at high conversion efficiency and low cost, using NG as feedstock. By converting NG to liquid fuels that can also be produced from renewable energy sources, we create a market-driven path to a sustainable energy future based on zero-net-carbon fuels. The RFRC will develop enabling technology and institutions including a technology roadmap and strategic business plan in the context of which new businesses can thrive. By providing seed funding for the RFRC the State of California can leverage its investment in energy research by joining with Iowa and Colorado in a significant endeavor that will attract sustaining support from federal and private sources.

**Appendices** Four appendices follow:

1. Tri-state alliance members
2. Affiliates
3. RD&D agenda—example
4. Nomenclature



## TRI-STATE ALLIANCE MEMBERS

Iowa Energy Center (IEC) – <http://www.energy.iastate.edu/>

Norm Olson, [nolson@iastate.edu](mailto:nolson@iastate.edu). Biomass and Alternative Fuels Program Manager; Chair, NH3 Fuel Association.

Colorado School of Mines (CSM) – <http://www.mines.edu/>

Jason Ganley, [jganley@mines.edu](mailto:jganley@mines.edu). Teaching Associate Professor, Chemical and Biological Engineering: alternative fuel synthesis and utilization; fuel cell systems; hydrogen production from renewable energy; series hybrid vehicle drivetrain design

Cal Poly State University at San Luis Obispo (CPSLO) – <http://www.calpoly.edu/>

William Ahlgren, [wahlgren@calpoly.edu](mailto:wahlgren@calpoly.edu). Associate Professor, Electrical Engineering: electric power; energy systems engineering; electrochemical energy conversion; photovoltaics; defect chemistry; thin film epitaxy; metal organic CVD

Paul Choboter, [pchobote@calpoly.edu](mailto:pchobote@calpoly.edu). Associate Professor, Mathematics: modeling complex systems

Dianne DeTurris, [ddeturri@calpoly.edu](mailto:ddeturri@calpoly.edu). Professor, Aerospace Engineering: propulsion systems; gas turbine power plants

Jeff Gerfen, [jgerfen@calpoly.edu](mailto:jgerfen@calpoly.edu). Lecturer, Electrical Engineering: digital electronics, embedded systems

Eugene Jud, [ejud@calpoly.edu](mailto:ejud@calpoly.edu). Lecturer, Civil and Environmental Engineering: sustainable transportation systems

Chris Lupo, [clupo@calpoly.edu](mailto:clupo@calpoly.edu). Assistant Professor, Computer Science: high-performance computing for physical system modeling

Art MacCarley, [amaccarl@calpoly.edu](mailto:amaccarl@calpoly.edu). Professor, Electrical Engineering: control systems; automotive electronics; electric and hybrid vehicles; alternative fuel vehicles

Jianbiao (John) Pan, [pan@calpoly.edu](mailto:pan@calpoly.edu). Associate Professor, Industrial and Manufacturing Engineering: packaging and thermal management of electronic systems, design of experiments, manufacturing process optimization and control

Dana Paquin, [dpaquin@calpoly.edu](mailto:dpaquin@calpoly.edu). Assistant Professor, Mathematics: multiscale modeling of complex systems

Richard Savage, [rsavage@calpoly.edu](mailto:rsavage@calpoly.edu). Professor, Materials Engineering: microelectronic and micromechanical systems fabrication

Greg Scott, [gscott02@calpoly.edu](mailto:gscott02@calpoly.edu). Assistant Professor, Chemistry: quantum computational chemistry; nanomaterials design and fabrication

Xiaohua (Helen) Yu, [xhyu@calpoly.edu](mailto:xhyu@calpoly.edu). Professor, Electrical Engineering: computational intelligence; control systems; digital signal processing

## AFFILIATES

NH3 Fuel Association (NH3FA) – <http://nh3fuelassociation.org/>

John Holbrook, [john.holbrook@charter.net](mailto:john.holbrook@charter.net). Executive Director. Formerly with Pacific Northwest National Laboratory. Dr. Holbrook is also head of NHThree LLC, a start-up developing Solid State Ammonia Synthesis.

Trevor Brown, [tb@trevorbrown.us](mailto:tb@trevorbrown.us). Strategy consultant, marketing and communications.

William J. Clinton Foundation – <http://www.clintonfoundation.org/>

Stephen Crolius, [scrolius@clintonfoundation.org](mailto:scrolius@clintonfoundation.org). Transportation Program Director, Clinton Climate Initiative (CCI). CCI develops projects that illuminate the economic viability of emerging climate-beneficial technologies. A key focus of the Transportation Program is low-carbon liquid fuels and propulsion systems that employ them.

Lawrence Livermore National Laboratory (LLNL) – <https://www.llnl.gov/>

Robert Glass, [glass3@llnl.gov](mailto:glass3@llnl.gov). Senior Scientist, Hydrogen Program Leader. LLNL is developing Nox sensors primarily for automotive applications; the technology can be adapted to also produce NH<sub>3</sub> sensors.

Argonne National Laboratory (ANL) – <http://www.mcs.anl.gov/>

Timothy Tautges, [tautges@mcs.anl.gov](mailto:tautges@mcs.anl.gov). Computational Scientist, Mathematics and Computer Science Division; geometry and mesh representation for modeling of complex systems

Space Propulsion Group (SPG) – <http://www.spg-corp.com/>

Arif Karabeyoglu, [arif@spg-corp.com](mailto:arif@spg-corp.com). President and CTO. SPG is developing ammonia-fueled gas turbine technology for stationary electric power generation.

Carbon Recycling International – <http://www.carbonrecycling.is/index.php?lang=en>

Paul Wuebben, [paul.wuebben@carbonrecycling.is](mailto:paul.wuebben@carbonrecycling.is). Senior Director, Renewable Fuels. Formerly Clean Fuels Officer of the South Coast Air Quality District (Los Angeles).

## RD&D AGENDA—EXAMPLE

Technology research development and demonstration (RD&D) priorities for the RFRC will be set based on a high-level system study and a coordinated business-technology strategic roadmap. Prior to completion of this initial planning activity, our example trigger markets suggest likely RD&D priorities. The example trigger markets are: (1) road transport local fleets; (2) railway locomotives; (3) marine propulsion; (4) mid-scale energy hubs; (5) base-load electric power. The following RD&D, offered here by way of example, are tasks are organized around these trigger markets.

This list is offered by way of example only. The example trigger markets and their technology needs require further review. The actual research agenda of the RFRC will be set based on a business and technology development roadmap which does not yet exist. The roadmap will be created through a rigorous process involving all affiliates and stakeholders. Creating this roadmap is the first and most important task to be undertaken by the RFRC.

### 1. Road transport local fleets

- 1.1 Conversion kits to convert existing gasoline-fueled vehicles to flex-fuel vehicles that can accept MeOH/DME.
- 1.2 Low-cost MeOH/DME storage and dispensing systems for deployment in the existing fuel retail distribution system.
- 1.3 Compact, low-cost, high-efficiency MeOH-to-DME conversion equipment for deployment at the appropriate places in the energy supply chain.
- 1.4 Fully flex fuel vehicles (F3Vs) based on small battery/ultra-capacitor energy buffers charged either from the grid or by small on-board ICE or GT engines fueled by MeOH/DME.
- 1.5 F3Vs designed with optimum cost-weight-range tradeoff to maximize consumer acceptance.
- 1.6 High-efficiency NH<sub>3</sub> and MeOH fuel cells. This enables the replacement of conventional combustion engines by zero-emission high-efficiency electrochemical engines.
- 1.7 F3Vs based on electrochemical engines (e.g. direct MeOH fuel cells—DMFCs) rather than ICEs or GTs; or on FC-GT hybrid systems.
- 1.8 Further development of the Mobil MTG process to produce high-energy density fuels from MeOH. Exploration of alternative processes that may be of higher efficiency or otherwise advantageous.
- 1.9 General study of the problem of a sustainable aviation component to the transport sector, including use of NH<sub>3</sub> as aviation fuel for relatively short-flight but heavily used corridors (e.g. San Francisco-Los Angeles and New York-Washington).

### 2. Railway locomotives

- 2.1 Low-emission combustion of NH<sub>3</sub> in gas turbines, boiler furnaces, and internal combustion engines. Gas turbines are the energy converters of choice for railway locomotives. The potential emissions from NH<sub>3</sub> combustion are NH<sub>3</sub> (fuel slip) and NO<sub>x</sub> (formed in any combustion process that uses air as oxidizer). Fortunately NH<sub>3</sub> itself suppresses NO<sub>x</sub> (the thermal de-NO<sub>x</sub> process), so minimizing emissions in NH<sub>3</sub> combustion is primarily a matter of controlling fuel-air ratio. Accomplishing this modest goal will enable the near-term conversion of conventional engines and combustors to run on NH<sub>3</sub> as fuel.

### 3. Marine propulsion

- 3.1 Gas turbines are again the energy converter of choice and low-NO<sub>x</sub> operation of these devices is the key technology challenge for use of NH<sub>3</sub> as fuel to propel NH<sub>3</sub> tankers.
- 3.2 MeOH-fueled gas turbines are of importance for very-near-term shipping applications other than NH<sub>3</sub> tankers.

#### 4. Mid-scale energy hubs

- 4.1 Gas turbines are again a key energy converter and low-NO<sub>x</sub> operation of these devices is the key technology challenge.
- 4.2 High-efficiency production of NH<sub>3</sub> and MeOH by electrolysis. This enables cost-competitive production of NH<sub>3</sub> and MeOH from wind, solar, other renewable, and even nuclear energy sources.
- 4.3 Demonstration energy hubs based on electric power, NH<sub>3</sub>, and MeOH with district heating and cooling to achieve ultra-high energy efficiency.
- 4.4 High-efficiency production of NH<sub>3</sub> and MeOH directly from solar energy, including both artificial and biological photosynthetic mechanisms. This is an alternative path to the cost-competitive production of NH<sub>3</sub> and MeOH from solar energy.

#### 5. Base-load electric power

- 5.1 Here the key combustion technology is simple low-NO<sub>x</sub> burners, an easier challenge than gas turbines. In a steam-cycle plant designed for NG as fuel, only the burners of the steam generator furnace need to be modified or replaced for operation using NH<sub>3</sub> as fuel.
- 5.2 NH<sub>3</sub> transport and storage systems. Although already mature, these technologies can be improved. Further, in the context of NH<sub>3</sub> as fuel, issues such as conversion of existing pipelines to NH<sub>3</sub> must be studied. Can existing NG and petroleum pipelines be converted to transport NH<sub>3</sub>? Or must parallel pipelines be built in the same right-of-way?
- 5.3 Pipes vs. wires. Electric power transmission capacity is a central issue as renewable energy sources account for an ever larger fraction of California's total energy supply. When is energy best transported as electric power in high voltage (ac or dc) lines? When might it better be transported in liquid fuel form, as NH<sub>3</sub>, in relatively low-pressure pipelines? Pipelines are invisible in the landscape; therefore it should be less difficult to gain approval for their construction from the communities through which they must pass. There are power-to-fuel inter-conversion efficiency issues that must be addressed; these include taking account of the value of storage capability (intrinsic to fuel) and other factors specific to the energy source and end-use.
- 5.4. Carbon capture sequestration and sale (CCSS). Here there are many options being researched and some in active commercial development. RSRC will focus on those options that take advantage of the economy of scale realized when CCSS is done at a few concentrated sites (very large NG-to-NH<sub>3</sub> conversion plants located near the gas fields, processing fuel at TW or even PW rates<sup>20</sup>) rather than at a large number of smaller dispersed CO<sub>2</sub> emission sources (ranging from kW-scale individual vehicles to GW-scale central-station electric power plants).

---

<sup>20</sup> SI prefixes: k 10<sup>3</sup>; M 10<sup>6</sup>; G 10<sup>9</sup>; T 10<sup>12</sup>; P 10<sup>15</sup>; E 10<sup>18</sup>.

## NOMENCLATURE

BEV	Battery electric vehicle
CARB	California Air Resources Board
CCSS	Carbon capture sequestration and sale
CEC	California Energy Commission
CI	Compression ignition
CNG	Compressed natural gas
CPSLO	California Polytechnic State University at San Luis Obispo
DDC	Dodecane, $C_{12}H_{26}$
DFX	Dual-Fuel Exchange
DME	Dimethyl ether, $Me_2O$ , $C_2H_6O$
E85	Fuel blend containing 85% ethanol
EC-1	A reformulated gasoline blend introduced by ARCO in 1990
EIA	Energy Information Agency
EPRI	Electric Power Research Institute
Et	Ethyl, $C_2H_5$
EtOH	Ethanol, ethyl alcohol, $C_2H_5OH$
FCI	Fuel carbon intensity
FCV	Fuel cell vehicle
FFV	Flex fuel vehicle
F3V	Fully flex fuel vehicle
GHG	Greenhouse gas
GT	Gas turbine
GTL	Gas-to-liquid
HEV	Hybrid electric vehicle
HHV	Higher heating value
ICE	Internal combustion engine
IDLH	Immediately dangerous to life or health
IFCI	Intrinsic fuel carbon intensity
IMO	International Maritime Organization
LCA	Life-cycle analysis
LHV	Lower heating value
mdIFCI	Methane-derived intrinsic fuel carbon intensity
Me	Methyl, $CH_3$
MeH	Methane, $CH_4$
MeOH	Methanol, methyl alcohol, $CH_3OH$
MTG	Methanol-to-gasoline
NG	Natural gas
NGO	Non-government organization
NIOSH	National Institute of Occupational Safety and Health
NO <sub>x</sub>	Nitrogen oxides
OFS	Open Fuel Standard
PHEV	Plug-in hybrid electric vehicle
RFRC	Renewable Fuels Research Center
SEMATECH	Semiconductor Manufacturers Technology Association
SI	Spark ignition; also <i>Système Internationale</i>
SOEC	Solid oxide electrolysis cell
SOFC	Solid oxide fuel cell
USCAR	United States Consortium for Automotive Research
WSPA	Western States Petroleum Association
ZEV	Zero emission vehicle