August 1994 NREL/TP-463-6504

Renewable Energy and Its Potential for Carbon Emissions Reductions in Developing Countries: Methodology for Technology Evaluation

Case Study Application to Mexico

David Corbus, Manuel Martinez, Louis Rodriguez, and Jason Mark

Prepared for
Climate Change Division
Office of Policy, Planning, and Evaluation
and
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National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by the Midwest Research Institute
for the U.S. Department of Energy
Under Contract No. DE-AC 36-83CH10093

NREL/TP-463-6504 UC Category: 1321 DE94011870

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Prepared under Task No. WF945440

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Preface

Growing awareness of the link between carbon dioxide emissions and global climate change has prompted an international interest in evaluating methods for carbon emissions reductions. Although developing countries currently account for a small percentage of global carbon emissions, they are expected to be major contributors to future worldwide carbon emissions because of their high projected energy growth rates; hence, it is important to include developing countries in strategies for worldwide carbon emissions reductions. One promising alternative for greenhouse gas reductions in developing countries is the deployment of renewable energy technologies (RETs).

The Analytic Studies Division of the National Renewable Energy Laboratory, in collaboration with the Solar Energy Laboratory of the National Autonomous University of Mexico (Universidad Nacional Autonoma de Mexico), prepared this report for the Office of Policy, Planning, and Evaluation and the Air and Energy Engineering Research Laboratory of the United States Environmental Protection Agency (EPA). This report provides a methodology to evaluate RETs for a given developing country and to estimate their potential carbon emissions reductions. In addition to identifying the most promising technologies that have the potential to reduce carbon emissions, this analysis evaluates the connection between technology assessment and project identification.

The authors wish to thank Michael Adler of EPA's Office of Policy, Planning, and Evaluation and Mike Maxwell and Dick Stearn of EPA's Air and Energy Engineering Research Laboratory for their advice and support. Although we have benefited from the assistance of these people, the authors alone are responsible for the contents of this report. Furthermore, the opinions expressed in this report are those of the authors and do not necessarily reflect those of the funding institutions.

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Executive Summary

Many projects have been proposed to promote and demonstrate renewable energy technologies (RETs) in developing countries on the basis of their potential to reduce carbon emissions. However, no uniform methodology has been developed for evaluating RETs in terms of their *future* carbon emissions reduction potential. This study outlines a methodology for identifying RETs that have the potential for achieving large carbon emissions reductions in the future, while also meeting key criteria for commercialization and acceptability in developing countries. In addition, this study evaluates the connection between technology identification and the selection of projects that are designed to demonstrate technologies with a propensity for carbon emission reductions (e.g., Global Environmental Facility projects). Although this report applies the methodology to Mexico in a case study format, the methodology is broad based and could be applied to any developing country, as well as to other technologies.

The methodology used in this report is composed of four steps: technology screening, technology identification, technology deployment scenarios, and estimates of carbon emissions reductions. The technology identification methodology uses a decision analysis process to identify the most promising technologies and was applied separately for both on-grid and transportation technologies. The use of a decision analysis tool resulted in an easy-to-implement methodology that could incorporate uncertainty and varying degrees of data specificity. The decision analysis process is based on six criteria consisting of weighted cost value (combining life-cycle and capital costs for a technology), resource availability, social acceptance, state of technology development, environmental impact, and infrastructure requirements. Although the analysis focuses on renewable energy technologies, alternative fuels that are not based on renewable feedstocks were included in the transportation category because of their high potential for carbon emissions reductions.

The four technologies with the highest ranking in the technology identification process for the on-grid category were geothermal, biomass cogeneration, wind, and micro-/mini-hydro. Compressed natural gas (CNG) was the alternative that received the highest ranking for the transportation category. If deployed in urban environments, such as Mexico City, CNG vehicles could significantly improve local air quality as well as reduce carbon emissions.

Deployment scenarios were developed for the four highest ranking technologies in the on-grid category (noted previously) and for CNG vehicles. The purpose of the deployment scenarios was to estimate the role that each technology might have in energy markets in the year 2025. Assuming that RETs are zero or near-zero carbon emitters, emissions reductions attributable to these technologies are directly linked to the market penetration estimated in the deployment scenarios. Based on the deployment scenarios, carbon emissions reductions were calculated for the different technologies and compared to one another. To show the variation of emissions reductions to sensitive parameters such as resource availability, both a high and a low emissions reductions scenario were evaluated, based on a high and low deployment of RETs.

The estimated reductions in fossil fuel energy use and carbon emissions in Mexico for the five technologies analyzed are summarized in Table E-1. The biomass cogeneration scenario results in the highest carbon emissions reductions, and the micro-/mini-hydro scenario results in the lowest reductions. Compared to the RET scenarios, the CNG vehicles scenario has a higher carbon emissions reduction per

unit of fossil fuel energy displaced because of the effect of fuel switching from oil to natural gas (the energy reduction is because of the higher efficiency of dedicated natural gas vehicles). The combined total of all emissions reductions from these five technologies results in a 7.6% reduction in *total* carbon emissions for Mexico in 2025 for the high scenario and a 5.3% reduction for the low scenario, as compared to the base case (i.e., 2025 emissions without any RET deployments).

Table E-1. Carbon Emissions and Energy Reductions for the Five Different Technologies Analyzed (in million tonnes carbon and petajoules)

	Carbon Emissions		Energy	
Technology	Low	High	Low	High
Biomass cogeneration	2.5	4.6	163	294
Wind	2.8	4.3	135	203
Geothermal	3.8	3.8	159	159
CNG vehicles	1.6	2.8	30	57
Micro-/mini-hydro	1.1	1.4	44	59
Total	11.8	16.9	531	772
Total percent reduction in carbon emissions and delivered energy for all of Mexico	5.3%	7.6%	4.2%	6.1%

Of the five technologies that ranked highest in the technology identification process, two--biomass cogeneration and CNG vehicles--were discussed in terms of example demonstration projects. The purpose of the example demonstration projects is to describe the important issues involved in the identification of meaningful demonstration projects for the most promising technologies.

An important assumption in our project identification was that carbon emissions reductions from the *current* project itself were not as important as the *future* emissions reduction potential of the technology that the project sought to demonstrate. In the project identification, it was important to examine the specific energy sector being served and the potential for market expansion for each technology. Other important considerations for project identification included infrastructure requirements, costs, and social acceptability issues. Specific examples of projects for biomass cogeneration and CNG vehicles are described on pages 26-29.

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Introduction

An important issue on the environmental agenda is the link between increased emissions of greenhouse gases and global climate change. As a result, strategies for reducing greenhouse gas emissions have been identified and have received growing attention from policy makers. Energy production and use, in particular, are important to consider because they are the largest source of greenhouse gas emissions.

Because of their high projected energy growth rates,[1] developing countries are expected to be major contributors to *future* worldwide carbon emissions;[2] hence, it is important to include developing countries in any strategies for worldwide carbon emissions reductions. Several United States organizations, including the Environmental Protection Agency (EPA), have been evaluating methods for greenhouse gas reductions in developing countries. Projects have been proposed to promote and demonstrate technologies that have a large potential to reduce carbon emissions in developing countries. However, no uniform methodology has been developed for evaluating technologies on a common basis in terms of their *future* carbon emissions reduction potential. This study seeks to address this need by developing a methodology to identify and evaluate renewable energy technologies (RETs) and their future carbon emissions reduction potential.

Given the recent international interest in global climate change, RETs have gained support as tools for reducing carbon emissions. For example, a variety of RET demonstration projects have been selected for funding through the Global Environmental Facility (GEF).[3] However, no methodology has been developed for comparing the key attributes (e.g., economic and environmental) of technologies that are competing for funding for demonstration projects. Moreover, many assessments of demonstration projects for greenhouse gas mitigation technologies have focused exclusively on the near term and failed to evaluate the total potential of technologies to reduce *future* greenhouse gas emissions. Because the goal of some funding mechanisms (e.g., GEF) is to promote technologies that will be economically competitive in the future and also have strong potential for greenhouse gas emissions reductions, the development of a methodology to identify these technologies for developing countries is important. Such a methodology could be used by organizations interested in evaluating or funding RET projects to reduce carbon emissions.

In addition to identifying the most promising technologies that have the potential to reduce carbon emissions for a given country, this analysis evaluates the connection between technology assessment and project identification. Important parameters to consider in the selection of RET project applications are discussed. Although this report applies a technology and project identification methodology to Mexico in a case study format, the methodology is general in nature and can be applied to any country. Furthermore, this analysis could be modified and applied to other technologies or other environmental issues (such as acid gas emissions).

[1] Although developed countries account for the majority of existing greenhouse gas emissions, the annual average growth rate in commercial energy consumption is projected to be 3.8%/year in developing countries through the year 2010, versus an estimated 1.2%/year for developed nations such as the United States [OTA 1991].

[2] Carbon emissions in the form of carbon dioxide are expected to make the largest contribution to global climate change (over 50%) in the year 2030 [World Resources Institute 1992] and are the only greenhouse gas considered in this report.

[3] Funding for the first three tranches of GEF projects, which has already been committed, was over a billion dollars. A large percentage of that funding went to projects that focused on reducing greenhouse gases, of which energy efficiency and RET projects were common.

Approach

This analysis focuses on Mexico as a key developing country and is the product of the joint activities of the National Renewable Energy Laboratory (NREL) and the Laboratorio de Energia Solar of the Universidad Nacional Autónoma de México (UNAM). Mexico was selected for the study for the following reasons:

- expectations of large increases in energy requirements and carbon emissions[4]
- interest on the part of federal and local governments and agencies in Mexico in renewable energy and environmental issues
- availability of existing data and projections of energy supply and demand
- existing relationships with research institutions and government agencies
- growing cooperation between United States and Mexican institutions in the public and private sector

Previous analyses have examined the role that energy efficiency can play in reducing carbon emissions in developing countries [Sathaye and Ketoff 1991]. The primary goal of this analysis is to construct a methodology for identifying promising RETs with the potential to satisfy the energy needs of developing countries while, at the same time, contributing to a reduction in carbon emissions.

To help identify the most promising technologies, an analytical methodology was constructed based on the main criterion of the analysis: maximum carbon emissions reductions. The methodology, shown in Figure 1, can be described as a "funneling" process by which a short list of technologies is identified out of a larger group of possibilities. As the analyst steps through this process, the analytical tools (technology screening and evaluation, deployment scenarios, carbon emissions reductions) become more rigorous, while the list of technologies becomes shorter.

[4] Carbon emissions are estimated to increase threefold by 2025 in Mexico [Sathaye and Ketoff 1991]. Mexico currently ranks ninth in the world in terms of its contribution to global greenhouse emissions [World Resources Institute 1992].

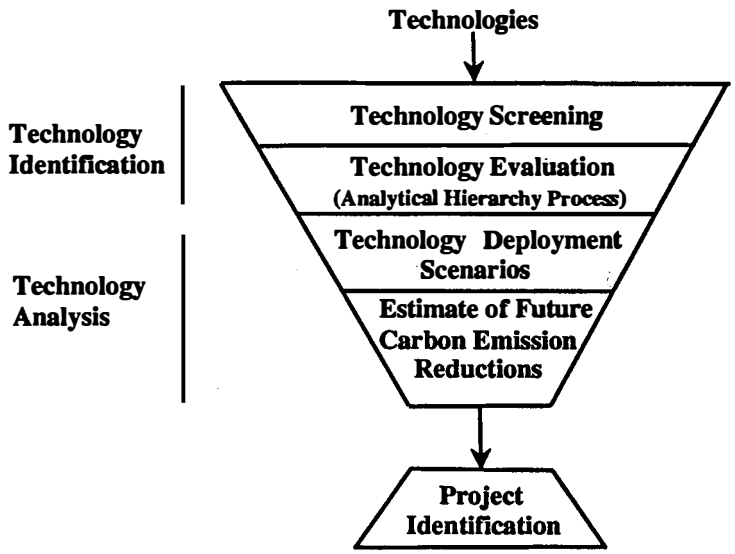


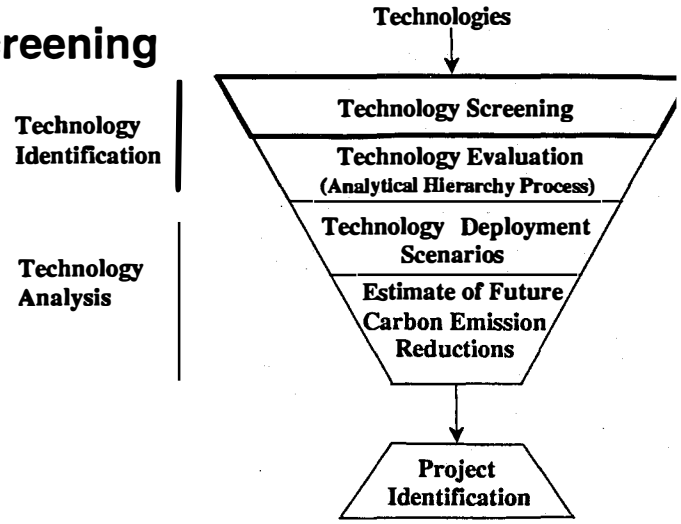
Figure 1. Analytical approach

The benefit to this approach, as opposed to having energy analysts select technologies based on their expertise, is that it allows technologies to be evaluated in terms of specific criteria, and it forces the analyst to consider these criteria when identifying technologies. These criteria include costs, social acceptability, infrastructure requirements, resource availability, state of development of a technology, and environmental issues. Both quantitative data (e.g., existing cost data) and qualitative information (e.g., social acceptability) can be combined in the technology identification methodology. Furthermore, the methodology evaluates the future energy end uses for technologies and the associated carbon emissions reductions attainable through the deployment of RETs for those end uses. Although our scenarios of RET deployments are very preliminary (in part because of a lack of sufficient information, such as resource assessment data), they do provide an order of magnitude estimate of the potential range of future carbon emissions reductions for different RETs.

Because many RETs are currently underdeveloped in energy markets, one of the primary goals of a strategy to promote their use is to demonstrate technical and economic feasibility through project applications; this also increases the knowledge base, operating experience, and overall user familiarity associated with a technology. Near-term projects that will help to commercialize RETs for the major energy end uses identified are therefore the focus of our project identification. Furthermore, a key assumption in our project identifications is that carbon emissions reductions from the project itself are not as important as the *future* emissions reduction potential of the technology that the project seeks to demonstrate, and this can be estimated from our preliminary RET deployment scenarios.

At present, global warming is not a major concern for most energy planners in Mexico. However, promoting cost-effective or near cost-effective RETs, particularly those that have the potential to further economic and social development *and* reduce carbon emissions, can be an effective energy strategy. The methodology contained in this report can help to achieve these goals.

Technology Screening



At the start of the project, more than 60 renewable energy technology/end-use combinations were defined as technically feasible in Mexico. In order to maintain a manageable technology identification procedure, UNAM reduced this list to a group of 13 technologies for further evaluation. Decisions to select technology/end-use combinations were based on the following criteria:

1. A technology from each major resource category (solar, wind, biomass, hydropower, geothermal) was chosen.

2. Only technologies that were expected to reach maturity in the near- to mid-term were considered (i.e., before about 2010).

3. A greater emphasis was placed on end uses that are major energy consumers in Mexico, because these are associated with the most significant carbon emissions.

Based on the criteria for technology selection and the project goal, it was determined that the utility and transportation sectors are primary areas of interest for RET applications. Electricity production and transportation consume half of the primary energy in Mexico and are thus key targets for emissions reductions.[5] The technologies that evolved from the screening are shown in Table 1.[6]

Table 1. Technologies Evaluated

On-Grid	Transportation
Biomass cogeneration	Ethanol from biomass
Mass burn of municipal solid waste	Methanol from natural gas
Micro-/mini-hydro	Compressed natural gas (CNG)
Biomass direct combustion	Methanol from biomass
Biomass gasification/gas turbine	
Wind	
Solar photovoltaic	
Solar thermal	
Geothermal	

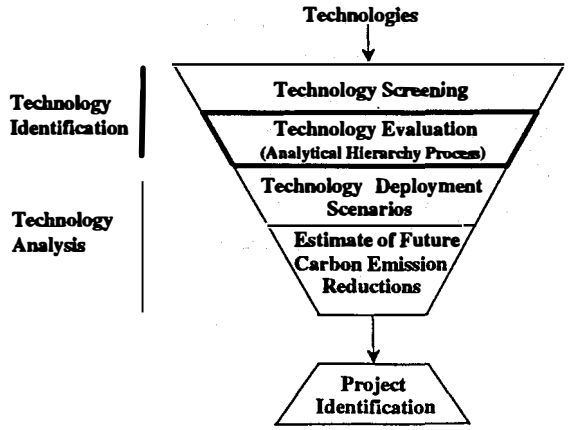
[5] Electricity production in 1987 accounted for 24% of primary energy demand, whereas the transportation sector accounted for 26% of the demand in that year [Sathaye and Ketoff 1991].

[6] Although compressed natural gas (CNG) is not a RET, it was chosen because it is a promising near-term alternative transportation fuel that has the potential to significantly reduce greenhouse gas emissions as well as other air pollutants.

Off-grid electricity technologies were not evaluated because such energy demand is small compared with on-grid demand. Although off-grid electrification is important for social development and RETs have great potential for non-grid applications, the ultimate goal of this analysis was to identify RETs with the greatest potential for carbon emissions reductions. Because off-grid electricity demand is low relative to on-grid demand, the potential to reduce carbon emissions through the deployment of off-grid technologies is relatively small compared with that of on-grid technologies.[7] (This assumes that in the *future,* off-grid electricity demand will be low compared to on-grid demand. Although this is presently the case, it could be different in the future.)

[7] Off-grid electricity demand was estimated to be four percent of the total electricity demand (the rest being on-grid). This percentage is projected to decrease in the future [Corbus, Mark, and Martinez 1993]. An evaluation of off-grid RETs and the subsequent carbon emissions reductions for different deployment scenarios could be a potential follow-up activity to this analysis.

Technology Evaluation–Analytical Hierarchy Process



After reduction of the technology list, a decision analysis tool called the Analytical Hierarchy Process (AHP) was next used to further characterize the technologies in a more rigorous manner. The AHP is based on the work of Saaty [Saaty 1980], who established an analytical hierarchy for problem solving. Background information on the AHP can be found in Appendix A.

The AHP, as used in this analysis, is a methodology for ranking technologies in terms of specific criteria that define a technology. These criteria may be quantitative in nature, such as specific cost data, or more qualitative, such as subjective assessments of the social acceptance of a given energy technology. Because the AHP process involves ranking the different criteria in terms of their overall impact on the potential success of a technology for the given project goal (i.e., a reduction in carbon emissions), the process involves some subjective decision making. In our analysis, subjective input to the AHP was based on the opinions of the UNAM researchers.

The AHP was a useful tool for this analysis because it uses both quantitative and qualitative inputs, hence it is flexible enough to incorporate specific data (such as technical or economic information) as well as more subjective factors. Furthermore, the AHP is a comparative methodology that incorporates a ranking methodology for different criteria, and this makes the analysis more manageable. Because we are interested only in *relative* comparisons of the different criteria, detailed data are not always necessary, and the data requirements are therefore lessened. Creating a methodology that did not require extensive data was important because it allowed the methodology to be relatively simple and easy to use. In addition, much of the data that would be required for a more extensive analysis are unavailable for Mexico (this is true for many developing countries).

The application of technologies across energy end-use sectors was not evaluated in the AHP analysis. Instead, two different end-use sectors, or categories, were evaluated–on-grid electricity and transportation–and the AHP analysis was conducted for specific technology/end-use combinations.

In our analysis, we used the AHP to identify the most promising technologies for carbon emissions reductions based on the criteria that we developed for technology evaluation. The following criteria were used: weighted cost value (combining life-cycle and capital costs for a technology), resource availability, social acceptance, state of technology development, environmental impact, and infrastructure requirements. Appendix A discusses how these criteria were evaluated for the different technologies within the structure of the AHP. Discussed below are the *results* of the AHP in terms of the six criteria.

Weighted Cost Value

As part of the AHP, a weighted cost value was used to investigate several key economic parameters. The weighted cost value takes four cost parameters–current, midterm (year 2010), and future (year 2025) life cycle costs, and near-term (year 2000) capital costs–and combines them, along with a series of weighting factors, in a linear equation that provides a single number for each technology (called the weighted cost value).

The life cycle cost for each technology was determined from the literature [OTA 1992, SERI 1990, SERI 1990a, EPRI 1986, SAIC 1990, DOE 1992]. Although life-cycle cost estimates inherently include capital costs, capital costs (c. 2000) were included as a separate technology parameter in the weighted cost value. The upfront capital outlays for a project, especially in a developing country such as Mexico where capital for large-scale energy projects can be scarce and the government's foreign debt is extremely high, are an important part of the overall investment criterion for a project. The capital costs ($/kWh) used in the weighted cost value are based on a typical size project for the given technology.

The use of the weighted cost value as an input to the AHP allows quantitative indicators of technology characteristics to be included in the subjective decision-making process represented by the AHP. By combining multiple technology parameters into one value, several characteristics can be considered without complicating the AHP by adding too many parameters. More detailed information on the weighted cost value may be found in Appendix B.

The different technologies within each category, listed in Table 1, were evaluated in terms of the weighted cost value criterion. Geothermal, biomass cogeneration, wind, and micro-/mini-hydro received the highest ranking for the on-grid analysis; compressed natural gas (CNG) and methanol from natural gas for internal combustion engine vehicles received the highest ranking for the transportation category. (It should be noted that average cost estimates were used for the weighted cost value and that costs are approximate and are based on technology goals; specific costs may vary for a given technology).

Resource Availability

The resource availability for a given RET, including the quantity and quality of the resource, has a direct effect on the energy output of a RET and can be a determining factor in the economic feasibility of a RET in a given region. A large resource availability for a technology indicates potential for a large technology penetration, assuming that other technology deployment factors (i.e., criteria considered in this analysis) are attractive. For the level of detail required for the technology identification process, resource availability on an aggregate national level is acceptable, although it should be noted that resource availability is extremely regional, and any evaluation of national resource availability is a generalization. In fact, resource availability for a given technology could be small in Mexico as a whole but extremely attractive in certain areas.

As is the case with many countries, available renewable energy resource data for Mexico are lacking in many areas. In general, resource availability for solar technologies was very high [Estrada and Barron 1991] as was the availability of wind [Elliot 1993] and biomass resources [Strategies Unlimited 1987] (based on the limited resource data available); projections of hydro and geothermal resources were based on government planning studies [SEMIP 1990].

Social Acceptance

Social acceptance includes both labor requirements and acceptance of the conversion technology. In general, existing systems are given a higher value because people are already familiar with them. This was particularly true for the transportation category because this sector requires a high degree of user interface with the energy service. Utility-generated electricity (i.e., on-grid), on the other hand, does not require the *user* to interface with a new energy system. However, *utility* acceptance of RETs, particularly with respect to power stability and intermittent constraints, is considered under the infrastructure criterion.

The potential for a technology to create jobs in Mexico, for both operation and maintenance of a technology as well as manufacturing and installation, is considered an important component of social development. The impact of land use requirements for a given technology is also considered under this criterion to the extent that it has an effect–perceived or real–on displacing valuable land with alternative uses, such as farmland.

Existing technologies, such as direct biomass combustors or cogeneration systems, were given high rankings. Similarly, in the transportation category liquid fuels (e.g., methanol and ethanol) were favored over CNG because of their consistency with existing fueling modes for gasoline. In the case of dedicated biomass crops, the use of land for energy crops can compete directly with the use of the same land for food crops; as a result, crop residues were primarily considered in the analysis of biomass technologies. Crop residues can also impact the local transportation infrastructure, but this was evaluated under the infrastructure criterion.

State of Technology Development

The following five categories were used to define a technology's existing state of development: (1) research: from basic principles to laboratory models; (2) demonstration: when technical feasibility has been shown, and economic feasibility is sought; (3) mature: the technology has economic feasibility under restricted conditions; (4) commercial: the technology is available and has been demonstrated to be economically viable; and (5) massive: the technology has penetrated the market and is a major contributor. (These categories were not evaluated for technology development specifically in Mexico.)

State of technology development affects a technology's penetration rate because a technology cannot be significantly deployed until it reaches the commercial phase. In general, technologies with a low state of technology development will start to penetrate the market later than a technology with a high state of technology development (all other factors equal); hence, by 2025, technologies with a low state of technology development will not be as widely deployed. This also has an important effect on the potential of a technology to be demonstrated in near-term demonstration projects, which can accelerate market deployment.

Biomass cogeneration and geothermal were considered massive technologies at present; wind, micro-/mini-hydro, PV, and biomass direct combustion were considered commercial technologies. In the transportation category, ethanol from biomass was considered a massive technology as a result of the ethanol-from-sugarcane process that is carried out in Brazil. Both CNG and methanol from natural gas were considered commercial.

Environmental Impact

This consists of ranking the technologies based on environmental considerations, including non-greenhouse gas air emissions, water emissions, and land use. The environmental criterion receives a low priority for the *on-grid* category because the majority of RETs considered all have low environmental impacts. Because the project goal is the identification of *RETs,* as opposed to all energy technologies, the difference in environmental impacts is relatively small (e.g., all RETs result in a significant reduction in carbon emissions). However, the environmental criterion receives a high ranking for the *transportation* category because of the benefits in urban air quality associated with alternative transportation technologies.

For the electricity-producing technologies, mass burn of municipal solid waste and biomass direct combustion received the lowest ranking because of the air emissions associated with their use. CNG was favored over ethanol and methanol fuels because of its lower carbon monoxide emissions and smog-producing hydrocarbons, even though its emissions of nitrogen oxides were higher. (Although the goal of the present analysis is to identify promising technologies with the potential to reduce carbon emissions in the year 2025, our model could be used to evaluate technologies for different environmental factors, such as the evaluation of acid gas air emissions or air emissions that are potential ozone depletors.)

Infrastructure

This includes the distribution systems for the end-use energy as well as the collection systems for the fuel. Also included under infrastructure for the on-grid category is whether a technology is intermittent or dispatchable. Utilities can count on dispatchable technologies for power at any time (with the exception of unplanned outages); however, they cannot always count on intermittent technologies because of variations in the resource, although utilities may have a fairly good approximation of when the resource, and hence power output, is available. In general, dispatchable technologies are favored over intermittent technologies because they are not subject to the intermittent constraints of the resource.

Biomass resources, by their nature, have a very low energy density compared to that of conventional fuels, hence the volume of resource needed for energy production is much larger than that of conventional fuels (e.g., coal). The low energy density of biomass restricts the distance that the resource can be economically transported. This can confine biomass energy production to the proximity of the resource and can restrict technology size because of the economics of recovering large quantities of a resource. Therefore, the accessibility of the biomass resource can largely determine its use. This could be a significant factor in Mexico, where biomass resources may be located in areas without easy access, and where the infrastructure requirements for transport of biomass can be important.

Dispatchable RETs, such as geothermal, were favored over intermittent technologies, except in the case of biomass, where fuel collection was an important requirement. Natural-gas-based transportation fuels (CNG and methanol from natural gas) were favored over biomass fuels (e.g., ethanol and methanol from biomass) because of the existing infrastructure for natural gas production. In addition, liquid fuels were favored over CNG because of their consistency with the existing fueling infrastructure for liquid fuels.

Technologies Selected for Further Analysis

The results of the AHP are shown in Figures 2 and 3 for the on-grid and transportation categories, respectively. Detailed information on how the rankings of the different criteria were combined to arrive at the results in Figures 2 and 3 is given in Appendix A.

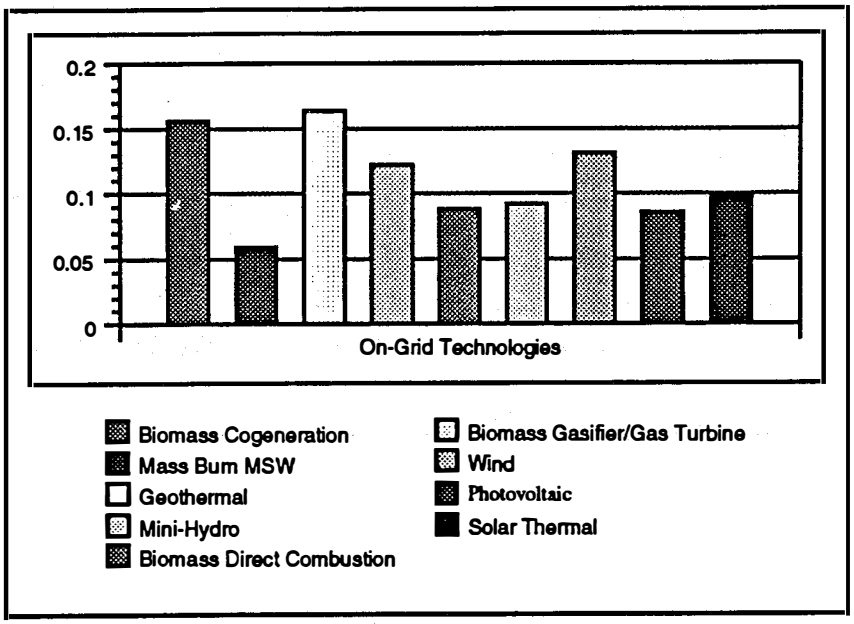


Figure 2. Composite priorities for on-grid technologies

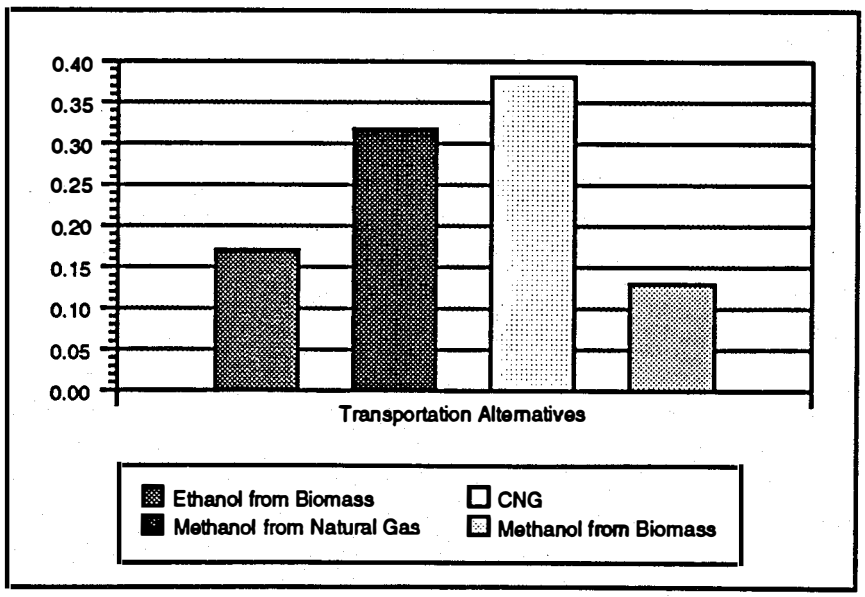


Figure 3. Composite priorities for transportation technologies

On-Grid

The four technologies with the highest ranking for the on-grid category were geothermal, biomass cogeneration, wind, and micro-/mini-hydro. These technologies all ranked relatively high for the four criteria that were considered the most important for the on-grid category: weighted cost value, resource, infrastructure, and state of technology development.

Among the four technologies with the highest rankings, geothermal had the highest ranking for the weighted cost value, with biomass cogeneration and wind ranking second and micro-/mini-hydro third. These four technologies also did well in terms of the state of technology development criterion, with geothermal and biomass cogeneration being considered technologies that have significantly penetrated the energy market (the highest ranking under state of technology development), and wind and micro-/mini-hydro being considered technologies that had demonstrated economic and technical viability (second highest ranking under state of technology development). Geothermal and biomass cogeneration also received the highest ranking for the infrastructure criterion; geothermal did well for this criterion primarily because it is a dispatchable RET and there are minimal fuel infrastructure requirements, while biomass cogeneration did well because much of the infrastructure for cogeneration is in place (many sugar mills have experience with some type of cogeneration). Solar technologies ranked the highest for the resource criterion, which was the second most important criterion, but they did not do well in many of the other criteria (e.g., weighted cost value), hence they were not among the four highest ranked technologies.

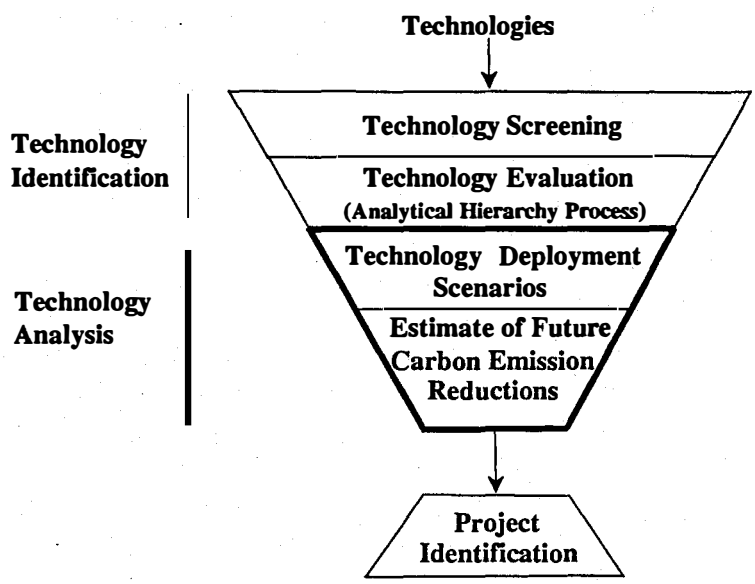
Transportation

CNG was the alternative that received the highest ranking for the transportation category. If deployed in urban environments, such as Mexico City, CNG vehicles could significantly improve air quality. Out of the four most important criteria for the transportation category (environmental impact, weighted cost value, social acceptance, and infrastructure, in order of importance), CNG ranked highest for the weighted cost value and environmental impact criteria. CNG did not do well in the social acceptance criterion because it is not consistent with existing fueling modes for vehicles. Because the positive aspects of an existing infrastructure for producing CNG offset the negative infrastructure requirements of not having a transportation fueling system in place and for requiring vehicle adaptations, CNG received an average ranking for the infrastructure criterion.

Methanol from natural gas received the second highest priority for the transportation category. The compatibility with existing fueling modes helped contribute to this ranking. Even though ethanol from biomass received the highest ranking for the state of technology development criterion (because of deployment in Brazil on a massive scale), ethanol from biomass still received a lower overall ranking than the non-renewable natural gas-based fuels.

Deployment Scenarios for Selected Technologies and Preliminary Calculation of Subsequent Carbon Emissions Reductions

Based on the results of the AHP as discussed in the previous section and in Appendix A, a smaller group of technologies was identified for further analysis. Deployment scenarios were developed for these technologies for the year 2025, and the subsequent carbon emissions associated with that deployment were estimated. Demonstration projects were then identified for the most promising technologies. A general discussion of the deployment scenarios and methodology for estimating carbon emissions reductions is given below, after which the results for the individual technologies are presented.



Deployment Scenarios

Given the larger goal of identifying technologies that could result in significant carbon emissions reductions, the purpose of the deployment scenarios is to estimate the role that each technology might have in future energy markets. Assuming that RETs are zero or near zero carbon emitters, emissions reductions attributable to these technologies are directly linked to their market penetration for a constant market size. Although our RET deployment scenarios are very *preliminary* (in part because of a lack of sufficient information, such as resource assessment data), they can be used for an order of magnitude estimate of the *potential range* of future carbon emissions reductions for different RETs.

Previous estimates of Mexico's current and future energy demand and supply mix [Sathaye and Ketoff 1991] are used as a base case from which renewable energy deployment scenarios are developed. These scenarios were constructed using technological, resource, and infrastructure data for Mexico. Because a rigorous economic analysis would require extensive market modeling and significant data requirements (much of the data are unavailable), economic factors are not directly considered in the scenario development out of consideration for creating a manageable methodology. However, the AHP and the ensuing project identification are heavily oriented around cost information.

STAIR Model

Based on our deployment scenarios, estimated deployment rates for specific technologies were input into the STAIR model [Sathaye and Ketoff 1991] to calculate carbon emissions reductions. STAIR (an acronym for the five end-use sectors that it assesses: service, transportation, agriculture, industry, and residential), is an accounting framework that provides a structure for assessing the impacts of energy demand, macro-economic factors, structural changes, efficiency improvements, and fuel switching on carbon emissions. Using estimates of current energy use in the five major end-use sectors as a starting

point, STAIR incorporates exogenous projections of future efficiency improvements and the mix of goods and services in each sector (e.g., the saturation of appliances or the production of steel) to estimate future energy consumption.[8]

We use future energy projections (year 2025)[9] for Mexico that are based on a study conducted by Lawrence Berkeley Laboratory (LBL) in which the STAIR model was used to estimate the reductions in carbon emissions achievable under specific energy efficiency scenarios [Sathaye and Ketoff 1991]. The STAIR model is used in our analysis as an accounting framework for estimating the reductions in carbon emissions that result from substituting RETs or alternative transportation technologies for fossil fuel technologies, based on our deployment scenarios and LBL's future energy projections. In some scenarios, the total energy consumption is also adjusted because of changes in the efficiency of a technology. For example, in the transportation scenario, the efficiency of dedicated CNG vehicles is greater than that of their gasoline counterparts; hence, for a given demand (i.e., vehicle miles travelled), less energy is consumed by CNG vehicles than by gasoline vehicles.

Dispatchable Versus Intermittent Technologies

As discussed previously in the section on infrastructure criterion for the AHP, dispatchable technologies and intermittent RETs are viewed differently by an electrical utility because a utility can always count on a dispatchable RET for power, whereas this is not the case with an intermittent RET. For utilities, capacity credits for intermittent technologies, such as wind turbines, are typically calculated as the fraction of each megawatt of windpower capacity that utilities can count on to displace conventional power sources during peak demand hours.[10]

In terms of capacity credits, a typical utility would benefit more from planning to substitute intermittent RETs for *peaking* or *intermittent* fossil-fueled power-generating technologies (e.g., natural gas turbines), as opposed to base power technologies. However, if a utility were to try to maximize its reduction in carbon emissions, it would try to substitute intermittent technologies for *base-power* generating technologies, such as coal-fired power plants, because this would result in higher emissions reductions. Practically speaking, the decision of which fossil fuel technology an intermittent technology would displace would be dictated primarily by resource considerations. For example, if the wind resource was high at nighttime when base-power generation was predominant, then an intermittent technology such as wind could displace some base-power generation.

The issue of which kind of generating power an intermittent technology displaces affects the avoided carbon emissions for that technology. For this analysis, we have made the simplifying assumption that intermittent technologies, such as wind turbines, displace 50% coal, 30% oil, and 20% natural gas, while dispatchable technologies, such as geothermal, were assumed to displace 100% coal. Coal-fired power plants result in the highest carbon emissions per unit of energy and are estimated to be among the most

[8] Although STAIR allows the user to assess the changes in total energy consumption and carbon emissions that result from modifications of key variables (such as the substitution of RETs for fossil fuel technologies), it does not provide the analytical methodology for actually generating these factors. These factors are developed as a result of the deployment scenarios.

[9] It should be noted that these energy projections were the only long-term (i.e., greater than fifteen years) energy projections available for Mexico.

[10] It should be noted that utility capacity costs are avoided only to the extent that RETs provide reliable peak power. This calculation involves a detailed knowledge of the resource for a given area. Utility capacity costs are not included in this study because the resource data are unavailable and because the study is not designed to go into such detail.

expensive fossil fuel technologies for base power generation in the future, so it is reasonable to expect that dispatchable RETs displace them. We have assumed that RETs would never substitute for hydro power because this would not result in any carbon emissions reductions and because the future cost of hydro power is estimated to be much less than that of fossil fuel electricity generation. Electricity generation in Mexico by fuel type for 1981 and 1987 and projections for 2025 (without the RET deployment scenarios) are shown below in Table 2.

Table 2. Electricity Generation in Mexico by Percent

	1980	1987	2025
Total (petajoule)	243	347	1334
Coal	0%	8%	25%
Oil	52%	61%	53%
Natural Gas	14%	8%	2%
Nuclear and Geothermal	1%	4%	8%
Hydro	33%	19%	12%

Source: Sathaye and Ketoff 1991

Discussed below are the deployment scenarios and the results of the STAIR modeling for geothermal, wind, micro-/mini-hydro, and biomass cogeneration, and for the CNG alternative transportation vehicle.

Results for the Different Technologies

Geothermal

Geothermal is a technology that has seen widespread development in Mexico. Currently, only 29% of the estimated 2.4 gigawatts (GW) of economically viable geothermal energy potential is being used [Mendoza, Masero, and Macias 1991]. Under current plans, this potential is expected to be completely exploited by the year 2010 [SEMIP 1990], although further exploration and technological advances may extend geothermal's potential contribution. Many geothermal resources are located on the Baja Peninsula in Mexico, which is not connected to the electrical grid in the rest of Mexico. However, it is anticipated that future arrangements between the United States and Mexico could facilitate the transfer of electricity from Baja Mexico via the United States grid to the rest of Mexico.

Our analysis assumes that Mexico's estimated 2.4 GW of geothermal potential is exploited by 2025. This is a conservative assumption because current plans call for this potential to be exploited by 2010. Moreover, additional geothermal reserves may be identified in the future, and future technologies may be able to utilize lower temperature geothermal reserves,[11] thereby expanding the potential of geothermal above the estimates used in our analysis.

[11] We have assumed that only flash steam hydrothermal geothermal technologies are deployed; binary cycle geothermal plants are able to utilize lower temperature reserves and hence expand geothermal potential, but resource information on low temperature geothermal reserves was not available [Goddard et al. 1989]. Geopressured geothermal reserves, as well as hot dry rock and magma systems, were not included in this analysis because they are still considered experimental technologies.

Table 3 shows the reduction in fossil fuel energy use[12] from geothermal electricity generation in 2025 and the annual avoided carbon emissions,[13] based on the displacement of electricity from a coal-fired power plant.

Table 3. Reduction in Fossil Fuel Energy and Avoided Carbon Emissions for Geothermal Energy in 2025

Reduction in fossil fuel energy (petajoules)	159
Avoided carbon emissions (million tonnes carbon)	3.8
Percent reduction in total Carbon emissions for Mexico	1.7%

Biomass Cogeneration

As of 1990, Mexico had installed nearly 3 GW of industrial cogeneration capacity, although all of this was used exclusively for on-site energy demand (i.e., not for sale to the utility grid) [SEMIP 1990a]. Projections indicate that an additional 1 GW may be installed by the year 2000. While cogeneration plays an important role in meeting industrial energy demand through the on-site generation of heat and power for process energy consumption, it also has the potential to make substantial contributions to total power supplies through the sale of electricity. Recent developments in the utility sector have opened the market for non-utility generators to sell electricity to the grid as a result of a willingness on the part of the federal utility to buy back power from industrial and commercial cogenerators.

Experience with the sugarcane industry worldwide (in places like Hawaii, Indonesia, Jamaica, Thailand, and Costa Rica) indicates that sugar mills have great potential to become net producers of electrical energy. Power sale provides an alternative revenue stream that strengthens the economic viability of an industry that is declining worldwide in the face of falling sugar prices. In addition, because sugar mills cogenerate using a renewable biomass fuel (sugar cane residue), enhanced power production in the sugar industry can have important benefits in reducing fossil energy dependence and lowering carbon emissions.

At present, sugar mills in Mexico generate just enough electricity and steam to meet their on-site energy needs. However, experience in other countries has demonstrated that operational modifications and technological improvements that permit reductions in on-site energy use and increase power generation capacity are economically viable [Mahin 1989]. Mexico is currently the eighth largest sugar-producing nation in the world, and projections indicate that milling capacity may almost double by 2025 [Sathaye and Ketoff 1991], thereby offering a large market for power generation. Assuming process improvements are implemented that reduce on-site energy demand, retrofits to the mill power plant to enhance the efficiency of power production, and the use of off-season fuels as a supplement to the residue typically

[12] This is the reduction in the energy supplied (as opposed to delivered energy), so it includes transmission and distribution losses, the efficiency of a coal plant (assumed at 34%), and the fuel losses during transport.

[13] Carbon dioxide emissions are reported as total carbon throughout this report. Carbon emissions for flash steam geothermal plants are estimated at 0.15 tonnes carbon per GWh, a very small amount compared to those for conventional fossil fuel technologies [Public Service Commission of Nevada 1991].

burned in a mill,[14] roughly 230 kWh of electricity can be sold for each ton of cane milled[15] [Larson et al. 1987]. Given projections of future sugar production in Mexico, an estimated 13,400 GWh of electricity could be sold to the grid in 2025 if 90% of the mills were to adopt the aforementioned changes to their plant operations. A lower estimate, which assumes that only 50% of the mills adopt these changes, indicates that 7500 GWh/yr could be sold in 2025. Table 4 illustrates the reductions in fossil fuel energy use and carbon emissions that would result if all of this cogenerated power were to displace coal-fired baseload power generation.

Table 4. Reduction in Fossil Fuel Energy and Avoided Carbon Emissions for Biomass Cogeneration in 2025[16]

	Low	High
Reduction in fossil fuel energy (petajoules)	163	294
Avoided carbon emissions (million tonnes carbon)	2.5	4.6
Percent reduction in total Carbon emissions for Mexico	1.1%	2.1%

Wind

There is a great potential for wind energy in Mexico which has, up to this time, been largely undeveloped. The attractive economic outlook for wind energy is one of the main reasons that this technology did so well in the AHP technology evaluation. Although wind energy projects are currently being installed for off-grid applications, future market conditions appear promising for the development of wind farms for on-grid applications.

Wind resource data for Mexico are limited; hence, for the wind scenario, simplified assumptions were made, based on the best wind resource information available. Because of the uncertainties associated with estimates of the wind potential in Mexico, a low and high scenario for wind technology deployment were developed. For the low scenario, it is assumed that 5.0 GW of wind capacity are installed by 2025, and for the high scenario, 10.0 GW is assumed.[17] The reductions in fossil fuel energy use and carbon emissions from wind power in 2025 are shown in Table 5 for both the low and high scenarios. Estimates

[14] Sugar mills currently burn the fiber left over after the juice is pressed from the sugar cane, called bagasse; however, this fuel is only available during the milling season. The cane tops and leaves are typically left behind or are burned in the field before cane harvesting, thus wasting a large amount of biomass that could potentially be collected for energy conversion. This analysis assumes that a portion of these tops and leaves are recovered and burned at the mill during the off-season to generate power (a portion is left in the field to replenish nutrients and to control erosion).

[15] Assumes both the bagasse and cane trash are used for power generation.

[16] Carbon emissions from biomass are not included in the total carbon estimates because it is assumed that biomass sequesters the same amount of carbon during its growth phase as is released on combustion, resulting in no net gain of carbon emissions. This assumption neglects carbon emissions associated with fertilizer manufacture and use, and collection and transportation of biomass.

[17] These scenarios are based on a preliminary estimated wind energy potential of 50 GW [Elliot 1993]; hence, the high scenario corresponds to 15% utilization of this potential, and the low scenario corresponds to 10%. No detailed analysis of the available land area for wind farms has been performed for Mexico to date, so the 10% and 15% assumptions are very preliminary.

are based on the displacement of 50% coal, 30% oil, and 20% natural gas. The scenarios are based on a capacity factor for wind of 30%.[18]

Table 5. Reduction in Fossil Fuel Energy and Avoided Carbon Emissions for Wind Energy in 2025

	Low	High
Reduction in fossil fuel energy (petajoules)	135	203
Avoided carbon emissions (million tonnes carbon)	2.8	4.3
Percent reduction in total Carbon emissions for Mexico	1.3%	1.9%

Power from wind is subject to intermittent fluctuations in the wind resource. While many of the problems of interfacing wind with utility grids may be overcome with specific hardware and design-related interconnection changes, stability and operability factors of utility generation will be affected by large deployments of intermittent technologies. For example, the load-following capability and operating reserve requirement of a utility may affect the maximum amount of wind power generation that can be incorporated into a utility generation mix without compromising normal utility operations. The maximum contribution of an intermittent renewable energy technology to the utility grid, based on stability and operability constraints, is known as the intermittent factor. It was assumed for this analysis that the amount of wind capacity deployed would not be greater than 25% of the power generating capacity of a given state within Mexico.[19]

Micro-/Mini-Hydro

Mexico's hydroelectric potential has been estimated at 80 terawatt-hours per year (TWh/yr), only 34% of which is presently being used [SEMIP 1990]. Current national energy plans call for a doubling of hydroelectricity capacity by 2010, primarily through the development of larger scale hydro projects (no forecasts are included in national energy plans for micro-/mini-hydro, hence it is assumed that the doubling of hydro power would be primarily from large-scale hydro plants). The environmental implications of large-scale hydropower plants, along with the conflicts generated by relocation of rural inhabitants, makes it unlikely that large-scale hydro capacity will be extended beyond the planned figures. However, possibilities exist for increased capacity through micro-/mini-hydro projects, which do not have the environmental and social problems associated with large-scale projects.

[18] Capacity factor is based on the amount of time that the technology will actually be producing electricity, and it is highly dependent on the wind resource and the technology design. Although a 30% capacity factor is well above average for today's wind turbines, improvements in technology design (e.g., advanced airfoils, predictive controls) should result in higher capacity factors for future wind turbines [Cavallo 1993].

[19] More specifically, estimates of electrical generating capacity for the year 2025 were calculated for states with a high wind potential based on the assumptions for future energy growth used in the LBL analysis [Sathaye and Ketoff 1991]. The total wind capacity assumed in our scenario was then allotted evenly to these states. These projections for wind capacity by state were then compared to estimates of 25% of the future state power generating capacities (i.e., an intermittent factor of 25% was multiplied by the future capacities to estimate an upper bound for wind penetration). Because the wind capacity by state was less than 25% of each state's projected future capacity, the wind capacity used in our analysis is not unrealistic in terms of an intermittent factor.

No consensus has been reached on the definition of micro-/mini-hydropower plants. In the United States, micro-hydro systems are sometimes described as those having capacities less than 100 kW, and mini-hydro systems as those ranging in capacity from 100 to 1000 kW, while small hydro power plants are those that produce between 1 and 30 MW of power [Moreira and Poole 1993]. We only consider micro- and mini-hydro systems in our analysis.

It was assumed for the low scenario that 15% of Mexico's remaining hydro potential after 2010 could be harnessed for micro-/mini-hydro systems. For the high scenario, it was assumed that 20% of this potential could be used.[20] Although the power supplied from micro-/mini-hydro power systems does vary according to seasonal fluctuations and shorter term weather phenomena such as dry and rainy periods, these systems are not considered intermittent technologies because their power fluctuations can be estimated in advance with a high degree of predictability. Therefore, we assume that micro-/mini-hydro power systems are dispatchable and that they displace base power emissions corresponding to a 100% coal-fired power plant. The reductions in fossil fuel energy use and carbon emissions from micro-/mini-hydro power in 2025 are shown in Table 6 for both the low and high scenarios.

Table 6. Reduction in Fossil Fuel Energy and Avoided Carbon Emissions for Micro-/Mini-Hydro Energy in 2025

	Low	High
Reduction in fossil fuel energy (Petajoules)	44	59
Avoided carbon emissions (million tonnes carbon)	1.1	1.4
Percent reduction in total Carbon emissions for Mexico	0.5%	0.6%

Compressed Natural Gas Vehicles

Transportation fuels have very different characteristics than the electricity-based RETs described above. It can be argued that because oil is cheap in Mexico and in abundance, alternative transportation fuels are not economical or practical. On the other hand, the development of alternative transportation fuels would allow Mexico to export more of its oil to pay off its high foreign debt while alleviating some of its severe urban air quality problems. Oil is the primary export earning commodity for Mexico and is thus a primary means by which the country can reduce its substantial external debt.[21]

[20] A doubling of the current hydro power in Mexico is estimated by 2010, resulting in 54.4 TWh hydro power (almost all of this would be large-scale hydro). Of the remaining 25.6 TWh of hydro potential (i.e., 80-54.4 TWh/year), it is assumed that 15% will be harnessed for micro/mini hydro power for the low scenario (3.8 TWh, 13.8 PJ) and 20% for the high scenario (5.1 TWh, 18.4 PJ). No estimate of the available mini or micro hydropower resources were available for Mexico; hence, the 10% and 15% estimates are very preliminary. For comparison, approximately 4% of the world's hydro potential is estimated to be under 2 MW [Water Power and Dam Construction 1989].

[21] Mexico's external long-term public debt was 41% of its gross national product in 1989 [World Resources Institute 1992]. Petroleum exports were 36% of total export earnings in 1990, and Mexico's debt service was 40% of its total export earnings [World Resources Institute 1992]; hence, about 15% of Mexico's debt was paid by petroleum exports.

Mexico's air pollution problem has become a key issue in the country's economic development, domestic politics, and international reputation. The Mexican government estimates that 40% of the country's air pollution is generated in the three major cities: Mexico City, Monterrey, and Guadalajara. The transportation sector accounts for about 85% of the air pollution in Mexico City, 65% in Monterrey, and 49% in Guadalajara [USAID 1992]. About 23% of the country's population lives in the metropolitan region of Mexico City, where air pollution is among the worst in the world.

Our deployment scenario for CNG vehicles is limited to Mexico City, Monterrey, and Guadalajara. Population growth for these three cities is assumed to be 1.7% annually through 2025. Car ownership is estimated to increase from 64 to 250 cars per 1000 people, while truck ownership is estimated to increase from 29.8 to 71.5 per 1000 people [Sathaye and Ketoff 1991]. The low scenario assumes that 50% of the cars and 50% of the gasoline trucks are replaced by *dedicated* [22] CNG cars and trucks in these three cities by the year 2025, and the high scenario assumes that 90% of the cars and gasoline trucks are replaced by dedicated CNG cars and trucks. It was assumed that dedicated CNG vehicles will reach an efficiency 15% greater than that of their gasoline counterparts by the year 2015.[23] The percentage of CNG vehicles that we assume in our scenario is very plausible compared to recent analyses of potential CNG vehicle deployments in the United States, but there are no specific assumptions underlying our percentages other than a desire to show a range of carbon emissions reductions. The reductions in fossil fuel energy use and carbon emissions for CNG vehicles in the year 2025 are shown in Table 7 for both the low and high scenarios.

Table 7. Reduction in Fossil Fuel Energy and Avoided Carbon Emissions for CNG Vehicles in 2025

	Low	High
Reduction in fossil fuel energy (petajoules)	30	57
Reduction in fossil fuel energy (million barrels of oil)	4.1	7.5
Avoided carbon emissions (million tonnes carbon) [24]	1.6	2.8
Percent reduction in total Carbon emissions for Mexico	0.7%	1.3%

Summary of Results

The reductions in fossil fuel energy use and carbon emissions for the five technologies analyzed are summarized in Table 8 in order of the magnitude of their emissions reductions. The biomass

[22] Dedicated CNG vehicles run only on natural gas, while dual-fueled vehicles, which have been *retrofitted* to run on CNG, also run on gasoline.

[23] Estimates are that by the year 2000, dedicated CNG vehicles will be 10% more efficient than their gasoline counterparts [Deluchi 1991]; it is assumed that this will reach 15% by the year 2025.

[24] This estimate is only for direct energy use and does not include greenhouse gas emissions (e.g., methane) over the total fuel cycle (such as emissions from natural gas extraction and transportation). The percentage change in the 100-year greenhouse gas carbon dioxide equivalent has been estimated at 13.8% lower for CNG vehicles as compared to gasoline vehicles [Deluchi 1991]. (It should be noted that there is large degree of uncertainty in current estimates of total fuel cycle emissions.)

cogeneration scenario results in the highest carbon emissions reductions, and the micro-/mini-hydro scenario results in the lowest reductions. Compared with the RET scenarios, the CNG vehicles scenario has a higher carbon emissions reduction per unit of fossil fuel energy displaced because of the effect of fuel switching from oil to natural gas (the energy reduction is because of the higher efficiency of dedicated natural gas vehicles). The combined total of all emissions reductions results in a 7.6% reduction in *total* carbon emissions for Mexico in 2025 for the high scenario and a 5.3% reduction for the low scenario.

Table 8. Carbon Emissions and Energy Reductions for the Five Different Technologies Analyzed (in million tonnes carbon and petajoules)

	Carbon Emissions		Energy	
Technology	Low	High	Low	High
Biomass cogeneration	2.5	4.6	163	294
Wind	2.8	4.3	135	203
Geothermal	3.8	3.8	159	159
CNG vehicles	1.6	2.8	30	57
Micro-/mini-hydro	1.1	1.4	44	59
Total	11.8	16.9	531	772
Total percent reduction in carbon emissions and delivered energy for all of Mexico	5.3%	7.6%	4.2%	6.1%

The *percent* reduction in carbon emissions depends largely on the projections for future energy demand that are used. A smaller energy demand estimated for the year 2025, for example, would result in a significantly larger percent reduction in total carbon emissions because RETs would compose a larger share of future energy supply. Because our assumption for energy use in the year 2025 assumes robust growth, projections for the percent of total carbon emissions reductions are conservative. For example, using LBL's low energy usage scenario[25] (which assumes significant energy efficiency measures), the percent reduction in total carbon emissions for the scenarios listed in Table 8 is 10.8% for the high scenario and 7.6% for the low scenario.

Because the comparisons of electricity generating RETs all use the same projections for future energy use, their carbon emissions reductions can be compared with one another. However, carbon emissions reductions from the scenarios are based heavily on the assumptions used, and the assumptions regarding

[25] LBL's high energy scenario results in 223 million tons of carbon emissions for Mexico in 2025, whereas the low scenario, which incorporates significant energy efficiency measures, results in 156 million tons of carbon emissions [Sathaye and Ketoff 1991]. However, the reduction in emissions from LBL's energy efficiency analysis and our analysis should not be directly compared because the LBL analysis includes major energy efficiency changes in all sectors, whereas our analysis only addresses the transportation sector and electricity generation.

resource availability, infrastructure, investment, policy, and related issues for the scenarios are not necessarily equal. For example, deployment of wind turbines as envisioned in this analysis would require Mexican utilities to incorporate significant amounts of intermittent power into their energy portfolios, necessitating changes in the way that they analyze capacity credits and energy investments, whereas the geothermal scenario would not require utilities to make any significant changes in the way they operate. The area of resource assessment is one area in particular in which additional data are needed for further analysis of RETs. The assumptions in the scenarios are all considered realistic (and some conservative) with regard to the potential deployment of the technologies by the year 2025, yet their impact on the estimated reductions in carbon emissions for a given technology should be noted.

Estimated Costs for Carbon Emissions Reductions

A range of future energy costs for different technologies are shown in Table 9 [OTA 1992; SERI 1990; SERI 1990a; EPRI 1986; SAIC 1990; DOE 1992; EPA 1990]. Based on these estimates, preliminary cost ranges for carbon emissions reductions, as shown in Table 10, were evaluated by dividing the difference between renewable energy and fossil fuel cost estimates[26] ($/kWh) by the annual amount of carbon displaced by a given RET.[27] Therefore, a positive cost number in Table 10 indicates the cost for carbon emissions reductions through the use of RETs, whereas a negative cost number implies that RETs will provide cost savings over conventional electrification (as well as reduced carbon emissions). Wind energy is intermittent and thus was assumed to compete as a fuel saver only; hence, it was compared only to fuel and variable operation and maintenance (O&M) costs for coal and natural gas, and no credit was given for potential capacity displacement. However, wind energy costs would be lower if a significant capacity credit were given. Because of the site- and utility-specific nature of wind capacity credits, it was not possible to incorporate these credits into the cost estimates.[28] Because of the large variation in estimates of the future costs of original equipment manufacturers (OEM) dedicated CNG vehicles, no cost estimates are given for carbon reductions for CNG vehicles.

Note that cost *ranges* are given because future cost estimates vary widely, depending on the source of the estimate. Fossil energy costs depend heavily on the assumptions used for future fuel prices, whereas costs for RETs are largely affected by variations in the resource and assumptions about future technology developments. Thus, the estimates should be viewed as rough indicators because of the inherent uncertainty associated with any estimates of future energy costs. Furthermore, energy cost estimates are based on electricity generation in the United States, because no estimates were available for Mexico for the technologies analyzed.[29]

Cost ranges for two time periods are shown in Table 10 to illustrate the trend in future energy costs. As with our estimates of carbon reductions, it is assumed here that dispatchable RETs would displace coal fired power plants and that wind would displace a mixture of base power and intermittent/peak power technologies (hence wind energy costs are compared with both coal and natural gas costs). In many cases, the cost for future carbon mitigation with RETs is positive, resulting in carbon emissions reductions as well as energy cost savings through the use of RETs. This is not surprising because of the emphasis placed on future technology costs in the weighted cost value criterion during the technology identification process.

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[26] The cost *range* was calculated by taking the difference between the highest RET and the lowest fossil energy cost estimate and the difference between the lowest RET and the highest fossil energy cost estimate.

[27] It was assumed that a coal generating plant produced 962 metric tonnes of carbon per GWh and that a gas turbine generating plant produced 484 tonnes carbon per GWh [San Martin 1989].

[28] Wind energy costs are based on an annual average wind speed of 5.8 meters per second (13 miles per hour); costs would be lower for sites with higher wind speeds.

[29] Although electricity costs vary widely between Mexico and the United States, the opening of Mexico's electricity market to private producers including the United States, as envisioned in the pending North American Free Trade Agreement, could bring future electricity costs for the two countries closer.

Table 9. Energy Cost Ranges for Technologies Analyzed (in cents per kWh in 1990$)

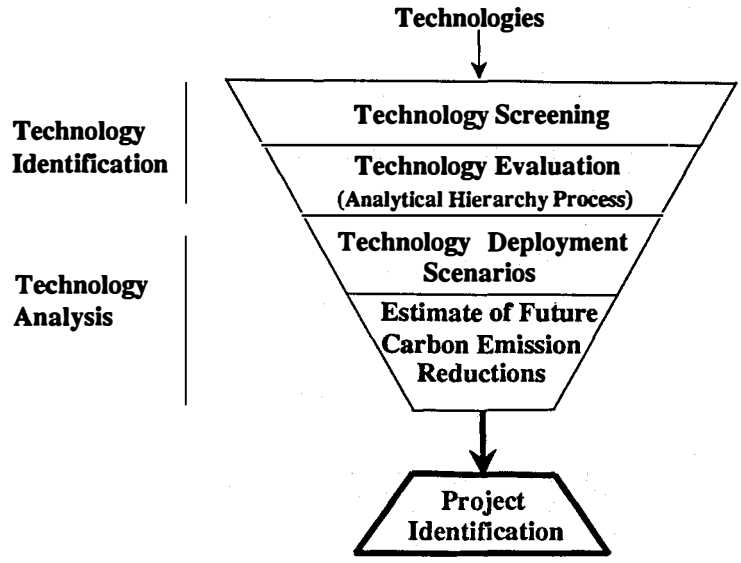
Technology	2000	2010
Base Power	5.3 to 6.0	5.5 to 6.3
Coal (variable costs only)	2.3 to 3.2	2.6 to 3.5
Gas (variable costs only)	4.7 to 8.5	5.2 to 10.2
Wind	4.6 to 5.4	3.8 to 4.8
Geothermal	4.6 to 6.5	4.5 to 5.9
Biomass-cogeneration	3.3 to 7.1	3.3 to 7.1
Micro-mini hydro	4.0 to 7.0	4.0 to 7.0

Table 10. Preliminary Cost Ranges for Carbon Emissions Reductions for the Four Different Renewable Energy Technologies Analyzed (in $ per tonne carbon in 1990$)

Technology	2000	2010
Wind/coal (variable costs only)	32 to 15	23 to 3
Wind/gas (variable costs only)	14 to -81	-8 to -132
Geothermal/base power	12 to -15	4 to -19
Biomass-cogeneration/base power	19 to -28	17 to -31
Micro-mini hydro/base power	18 to -21	16 to -24

Identification of Demonstration Projects

Overview



The results of the technology identification and analysis methodology have indicated which RETs have the greatest potential for achieving the largest carbon emissions reductions in the future, while also meeting key criteria for commercialization and acceptability (i.e., the AHP criteria such as costs and infrastructure requirements). These are technologies that are of primary interest for near-term demonstration projects to illustrate technological feasibility and serve as a vehicle for introducing technologies into the Mexican market. Funding for demonstration projects could come from the Global Environmental Facility (GEF) or other funding agencies. In some cases, such as with geothermal power, technologies have already matured to the point of market penetration, although market enhancement activities could still be undertaken to further their deployment.

The role of demonstration projects is to gain experience and knowledge about a technology through applications, as well as to increase the acceptability of a technology. These key criteria are taken into consideration in the project identification analysis. For example, O&M requirements for a demonstration project are important to consider. Locating a project in an area in which sufficient O&M experience is lacking for a given technology could severely hinder the success of a project and alienate newcomers to the technology, yet locating this same project in an area with adequate O&M experience could create expectations of job opportunities for future technology deployments.

Technologies Selected for Project Identification

Our project identification analysis focuses on technologies that did well in the AHP evaluation and that resulted in significant carbon emissions reductions in our deployment scenarios. Demonstration projects are identified for technologies that would contribute to the commercialization of a technology with a high potential for long-term carbon emissions reductions (as a result of our carbon emissions reduction evaluation). The economic benefits of the future carbon reductions could justify near-term project funding to help accelerate commercialization of a technology.

Of the five technologies analyzed in the previous section, two–biomass cogeneration and CNG vehicles–were selected for example demonstration projects. These examples are presented in the next section.

Guidelines for Project Identification

An important assumption in our project identification was that carbon emissions reductions from the project itself were not as important as the future emissions reduction potential of the technology that the project sought to demonstrate. Although demonstration projects are often evaluated in terms of their existing carbon emissions reductions, projects are usually small and hence do not contribute to a significant reduction in a country's overall carbon emissions. Therefore, what is important is the *future potential of a technology to be deployed on a large scale and hence result in a significant reduction in carbon emissions.*

In the project identification, it was important to examine the specific energy sector being served and the future potential for market expansion for each technology. Other important considerations for project identification included infrastructure requirements, costs, and social acceptability issues.

In some cases, near-term applications of a technology that were not estimated to be the major energy end-use in the future were considered. For example, a RET that was evaluated for on-grid utility power generation could be included in a demonstration project for off-grid village electrification if it was cost effective and achieved most of the goals that the on-grid demonstration project would achieve.

Another factor that was evaluated in our project selection was the overall size of a project, because this has a great impact on project cost. For example, smaller electricity generating plants are generally more costly per kilowatt than their larger counterparts because of the cost savings associated with economies of scale. Yet smaller plants can often demonstrate a technology's merit and feasibility while qualifying for funding that larger plants may not be eligible for because of limits on project funding.

There is a natural overlap between some of the analysis that was required for project identification and work that would be required to actually propose a demonstration project. For example, although our *examples* of demonstration projects do give an overview of specific applications, an agency that wanted to fund a demonstration project would require a more thorough analysis of the prefeasibility[30] issues involved with a demonstration project. Our project identifications are by no means intended to supplant the additional work that would be required for a prefeasibility analysis; they are primarily intended to be a screening process to illuminate issues associated with general project identification, as exemplified by the methodology presented in this report, and to provide enough information for someone wanting to develop a prefeasibility analysis from them. Figure 4 shows the relationship between the project identification discussed in this report and the follow-up work that might be associated with the prefeasibility evaluation of a technology for any given country.

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30 *Prefeasibility* is used here to indicate a study that would present a more detailed breakdown of plant costs and sizes based on in-depth resource information on a regional basis, and it would include general institutional factors that affect funding, such as utility policy for buying private power in a given region. A *feasibility* analysis would include detailed life cycle cost estimates for a given plant configuration, size, and site.

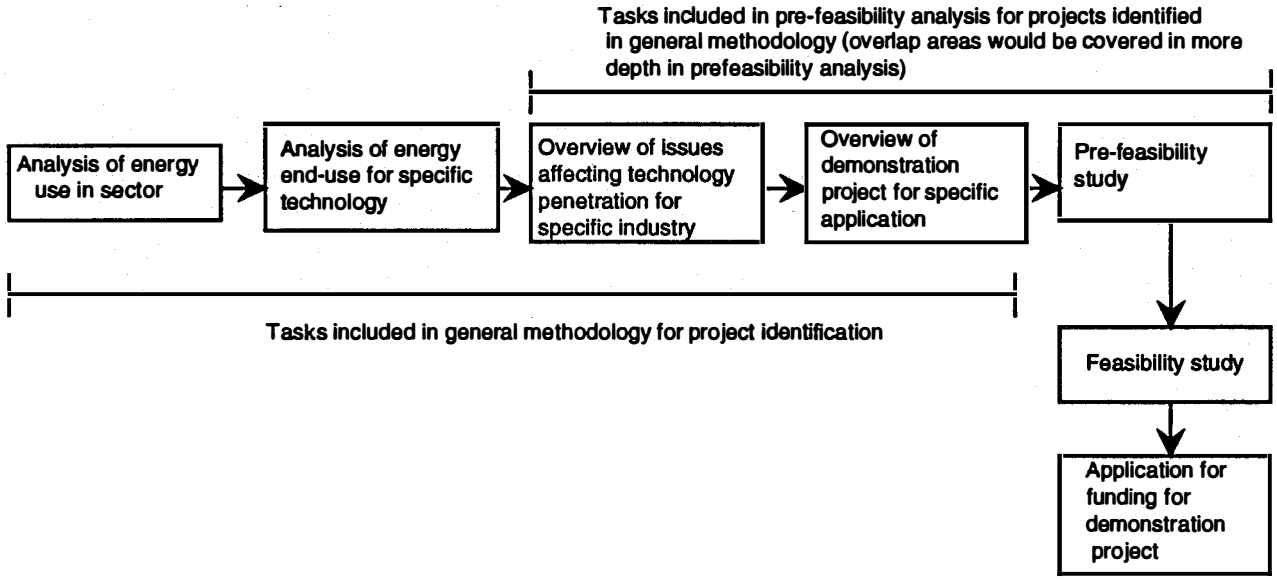

Figure 4. Relationship between general methodology for project identification and prefeasibility analysis

Example projects for biomass cogeneration and CNG vehicles are discussed below. The goal of these examples is to show the connection between the technology analysis discussed previously and the issues involved with the selection of demonstration projects.

Example of Biomass Cogeneration Project

Projects demonstrating the technical and economic feasibility of selling power from the sugar industry have been undertaken in several countries in recent years [Mahin 1989]. These projects have ranged from simple mill improvements, such as minimizing steam losses, to extensive retrofits of process and power generation technologies. In addition to technological modifications, such projects can also include changes in mill operations. For example, a small amount of incremental power generation can be achieved just through process and technological improvements in a mill that operates only during the cane crushing season; however, larger quantities of power can be sold if the mill were to operate year round, using a fossil fuel (e.g., oil) as a boiler fuel in the off-season. This type of operational configuration increases power sales at a typically low cost (assuming fossil fuel prices are moderate). Finally, the most extensive type of operational change would involve operating the mill year round using cane trash in the off-season as the primary boiler fuel. This type of configuration is not widespread, in large part because the requisite changes in trash harvesting and storage are largely unproven and often considered uneconomic. Nonetheless, the example project outlined here seeks to demonstrate this last category of operational changes, because it has the largest potential returns in terms of overall carbon emissions reductions.

A typical mill in Mexico is moderate to small in size compared with those found in the United States. This analysis assesses a mill crushing approximately 190 tonnes of cane per hour (processing rates in the United States are on the order of 300 tonnes per hour). The conventional power generating equipment, which includes a low pressure boiler and a back pressure turbogenerator, is replaced with a more efficient

high pressure boiler and a condensing extraction steam turbine with a greater electricity generating capacity. At the same time, steam use in the mill is reduced through the use of an advanced juice heater, falling film evaporators, and a continuous vacuum pan. These process energy reductions allow the turbogeneration system to generate large quantities of excess power while still meeting mill energy demands. Finally, to extend the amount of biomass energy converted to electricity by the mill, cane trash (tops and leaves) is collected for use during the non-milling season. Typically, cane trash is left on the ground or burned in the field; however, research indicates that about half of the trash can be harvested without negative impacts of erosion or nutrient loss [Phillips 1986]. The trash is baled and stored for use in the off-season as a boiler fuel in a manner similar to that used for the bagasse that is burned during the cane milling season.

The economic viability of such a project depends largely on several key variables, most importantly the retrofit costs and electricity buy-back rates. The capital investment required for mill retrofits and cogeneration equipment for this example is estimated at over $60 million (1992 dollars),[31] which is at the high end of estimated costs for other projects of similar size.[32] These costs must be offset by revenues derived from electricity sales, which vary from location to location. Although the details of electricity sales from private electricity producers, including the prices, are currently under negotiation in Mexico, it is assumed in this example project that electricity could be sold by private producers at prevailing industrial electricity rates. In the southern portion of Mexico, where a large number of mills are located, these rates are only 4.07¢/kWh for base power and 6.51¢/kWh for peak power [USAID 1992]. Such low buy back rates would make the possibility of achieving adequate returns on the project investment difficult. However, estimates of power generation costs for similar sugar industry cogeneration projects have ranged from 3.6-7.6 ¢/kWh (1992 dollars) [Mahin 1989], which would make such a project at least marginally economic in the current Mexican utility environment.[33]

Nevertheless, this example project, as currently configured, would probably not be able to receive financing. This is largely a product of the high initial capital cost combined with the low prevailing electricity buy-back price. In addition, there is very little experience with the trash harvesting and off-season operation activities proposed in the project design. On the other hand, the potential returns from this project are great. A full costing of the price of electricity (that removes current subsidies) might indicate that the project is in fact economically feasible. Also, because the mill retrofits were designed to maximize power sales, the fossil energy displaced by mill sales of electricity is potentially very great. This will result in large carbon emissions reductions, as demonstrated in earlier sections of this report.

Perhaps more important, a demonstration project configured similarly to the example provided here would help add to the information base on sugar industry cogeneration. In doing so, the project would facilitate the widespread implementation of these systems and help them realize their full potential, as outlined in previous sections. Demonstration of the trash harvesting and off-season mill operations as well as increased operational experience with energy-efficient mill technologies is critical to the future prospects of advanced cogeneration in the sugar industry. In particular, these demonstration and

[31] Capital costs are calculated based on estimates for the mill retrofits, turbogenerator, and cane trash handling equipment, derived from the work of Larson's group[Larson, et al. 1987].

[32] Costs for similarly sized projects have been estimated at $20-60 million (1992 dollars, scaled using the GDP deflator) [Mahin 1989].

[33] Current electricity rates are priced below cost in Mexico, and pressure from multilateral creditors has been forcing the utility to move toward higher prices that reflect the actual cost of generation. Therefore, as prices continue to rise, projects such as this will become even more economically attractive.

development activities can provide an important near-term stepping stone toward implementing gasification/gas turbine technologies that hold great promise for the industry in the mid- to long-term. The project would also play an important role in demonstrating electricity buy-back agreements between industrial cogenerators and the federal utility. Increased experience with non-utility generation may expand the window of opportunity for independent power production and small-scale generation, thereby opening avenues for further renewable technology penetration.

This project example is only designed to illustrate how cogeneration in the Mexican sugar industry might develop. Further research on mill operations would be required before actual projects could be identified. This is, in fact, the purpose of an ongoing project sponsored by the United States Agency for International Development (USAID). Under USAID funding, Winrock International is conducting surveys of the sugar industry in Mexico to identify promising areas for development activities.[34] After this initial screening, pre-investment studies will be undertaken for specific mills. This type of activity is a logical follow-on to the example projects identified in this report.

Example of CNG Vehicles Project

There are an estimated 700,000 light-and heavy-duty CNG vehicles in operation in the world today, of which 300,000 are located in Italy, and 110,000 are in New Zealand [Interagency Commission 1990]. In the United States, there is a growing number of CNG vehicles, although only about 30,000 were in use in 1988. Almost all of these vehicles are aftermarket conversions of conventional vehicles to dual-fuel vehicles that can run on natural gas or gasoline. Although there are only a small number of dual-fueled CNG vehicles in use in Mexico, the deployment of large fleets of CNG vehicles could have a significant impact on air quality in regions suffering from poor air quality, such as Mexico City, and it would also reduce carbon emissions and make more oil available for export.

Costs for alternative fuel vehicle deployments are primarily composed of expenses related to fuel feedstocks, fuel production and distribution, and vehicle technology. Except for the fact that it must be compressed for on-board storage, natural gas can be used directly from the present gas delivery system without processing; hence, the cost of natural gas for motor vehicle use consists of the base cost to transportation sector customers, plus costs for any extensions required to serve fueling stations, additional refueling equipment costs, and motor fuel taxes. Compared to gasoline vehicles, the additional costs for the deployment of CNG vehicles in the major cities of Mexico would consist primarily of costs for refueling stations and vehicle conversion. Incremental costs for production and initial distribution of natural gas would be similar to existing costs for natural gas, because Mexico has a plentiful supply of natural gas, and pipelines are available in the major cities.

Refueling stations for CNG vehicles take natural gas from pipelines at pressures of up to 100 p.s.i. (0.69 Pa), compress it to between 3000 and 3600 p.s.i. (20 and 25 Pa), and deliver it to the high-pressure tanks of CNG vehicles [United States DOE 1990]. The major costs for the refueling stations are for compressors, gas storage tanks for peak period demand, and the metering and dispensing system [Interagency Commission 1990]. The total cost for conversion of an existing public service station to

[34] Although the purpose of the example provided in this analysis was to demonstrate a near-commercial system with *mid-term* potential (keeping the goal of maximum carbon emissions reductions in mind), the USAID study is focussing on *near-term* opportunities for development. Nonetheless, the two projects have identified similar end-use/technology combinations as important for development/demonstration activities.

CNG refueling capability has been estimated at $233,000 to $462,000 (1992$) [United States EPA 1990].[35] Another source estimated the cost at $375,000 for a capacity of 300 vehicles per day and a peak rate of 30 vehicles per hour. These estimates assume no extra cost for land and conversion of an existing pump at a service station [United States DOE 1990].

The other major cost for the deployment of CNG vehicles is the cost of retrofitting the vehicles themselves, or in the case of a dedicated CNG vehicle, the extra cost of a CNG vehicle over its gasoline counterpart. Dual-fueled vehicles, which have been retrofitted to run on CNG, are much more common than dedicated CNG vehicles. However, costs for CNG conversions are significantly higher than the incremental OEM costs for producing dedicated CNG vehicles. Moreover, dual-fueled vehicles suffer from some loss of acceleration because of the added weight of the CNG tanks and because of an effective loss in engine displacement.[36] Current cost estimates for retrofitted CNG conversions range from $1,800 to $3,700, depending on vehicle size and the number of vehicles converted, while estimates of incremental OEM costs are on the order of $930 per vehicle (1992$) [Interagency Commission 1990].

This example project consists of the purchase of a significant number of dedicated CNG vehicles for use in fleets in the three cities with the worst air pollution in Mexico: Mexico City, Monterrey, and Guadalajara. Although Mexico City has by far the worst air quality in Mexico, Monterrey and Guadalajara also suffer from air pollution problems, and implementing demonstration projects in these other cities serves to widen the scope of the project and provide increased operational experience. The deployment of a limited number of CNG vehicles, as envisioned in this demonstration project, will have virtually no impact on air quality or carbon emissions reductions in Mexico City because of the large number of cars in Mexico City (about 3 million); hence, the emphasis is on demonstration of the technology for future deployments.

Although the exact configuration of fleet vehicles and refueling stations and their location would depend on the results of a prefeasibility analysis, an initial project example consists of the deployment of 6000 dedicated CNG fleet vehicles in Mexico City and 2000 vehicles in Monterrey and 2000 in Guadalajara, as well as the retrofit of six service stations for CNG refueling capability in Mexico City and two stations in both Monterrey and Guadalajara. It is assumed that vehicles are refueled every 3.3 days and that a refueling station could accommodate 300 vehicles per day at a peak rate of 30 vehicles per hour. The costs for the project would be about $3 million for the 10 refueling stations ($300,000 per station) and about $9.3 million for the OEM incremental costs for the CNG vehicles, resulting in a total project cost of $12.3 million.[37]

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[35] These costs are for fast-fill CNG fueling stations, where refueling times would be roughly equivalent to that of refueling a gasoline vehicle; slow-fill fueling stations are less common and would have different costs associated with them. A price inflator of 1.17 has been used to convert 1989 costs to 1992 costs.

[36] This results because gaseous fuels, unlike liquid fuels, displace air in the cylinder; the result is a loss in acceleration of as much as 30%. However, dedicated CNG vehicles can use optimized engines that take advantage of the high octane number of the natural gas and have minimal power loss compared to that of the engines they are replacing [Interagency Commission 1990].

[37] It should be noted that OEM costs for CNG vehicles are approximate and vary widely depending on the number of vehicles purchased and the marketing agenda of the company supplying the technology. Companies will vary in the amount of costs they absorb for OEM CNG vehicles, and companies could range from passing on all the additional costs to the consumer to none of the costs; our estimate for incremental OEM costs appears to be average.

This project example is designed to illustrate how CNG vehicles might contribute to improving air quality in Mexico while helping to reduce carbon emissions. Further research on air quality issues and transportation alternatives would be necessary before an actual project could be identified. A logical follow-up to the example project identification described here would be an assessment of the impact of alternative fuels on Mexico City's air pollution basin.

Conclusions

This study outlines a methodology for identifying promising RETs that have the potential to satisfy future energy demands in developing countries while, at the same time, contributing to a reduction of carbon emissions. The results of this methodology can be used to identify demonstration projects for the technologies identified. Although this report has applied the methodology to Mexico in a case study format, the methodology is general in nature and can be applied to any developing country.

Applications of Methodology

The methodology developed in this study could be used by international funding agencies, such as the Global Environmental Facility program of the World Bank, to evaluate renewable energy demonstration projects for a given country. Alternatively, the methodology could be used by in-country energy planners to help formulate long-range energy planning for RETs and access their potential carbon emissions reductions. The methodology takes an important step in providing a tool for energy planners to evaluate both the economic viability of RETs and their potential to reduce future carbon emissions (or other environmental issues of interest). Because there are many mitigation options for reducing carbon emissions, this type of assessment tool could provide a basis for funding decisions.

The methodology contained in this report can be used to identify demonstration projects for RETs. It can also be used to explore the interconnection between initial project identification and prefeasibility analyses for a given technology. For example, an initial project identification could lead to the conclusion that more information is needed to assess specific issues for a technology, such as resource, policy, financing, and infrastructure issues. These issues are typically addressed in a prefeasibility analysis. The initial project identification could lead to different recommendations regarding follow-up work, including (1) determination of the issues that should be examined in a subsequent prefeasibility analysis, (2) the conclusion that enough information exists (e.g., existing prefeasibility analysis or related information) to proceed with specific project identifications and funding proposals.

Application to Mexico

The current focus of energy planning in Mexico is not oriented towards lowering carbon emissions, but rather towards furthering economic growth and social development. However, recent developments have been undertaken to improve environmental conditions not related to carbon emissions reductions, and many of these developments impact the way energy is used. For example, the Mexican government has embarked on a multi-billion dollar air pollution control program that emphasizes the production of clean fuels, the installation of catalytic converters, and improved automobile efficiencies. The government's priority is to substitute low-sulfur fuel oil and coal for pollution from industrial (including power generation) sources (USAID 1992).

The role of carbon emissions reduction strategies in Mexico's future energy planning remains unclear. The uncertainty surrounding the issue of global warming weakens the incentive to develop policy initiatives addressing carbon emissions reductions. In addition, because the potential for global warming is perceived as a long-term phenomenon, near-term needs for energy planning are perceived as much more important. These are only a few issues that impact how carbon emissions reduction strategies are

addressed in Mexico (or in most countries for that matter). However, there is a sense in many countries, both developing and developed, that promotion of cost-effective and acceptable energy alternatives that lower carbon emissions is a prudent course of action, particularly because these alternatives usually result in other important benefits, such as a reduction in other forms of pollution.

Policy and political issues, in addition to the prefeasibility issues described previously, are also important factors governing the long-term commercial success of any given technology in Mexico. These issues include the following: limits on private electricity production; subsidized energy prices; the well established institutional infrastructure based on supply-oriented energy planning; the concentration of energy production in two large, state-owned companies–PEMEX and CFE–and the specific structural and institutional changes that these organizations need to make to encourage RETs; and the fact that many consumers are misinformed about energy technologies. Although this report has not considered the political and policy issues surrounding the deployment of the RETs identified in this report, these are extremely important issues that affect technology development.

Future Work

Future work on the development and application of the methodology presented in this report will be directed at applying the methodology to other countries. There is interest in Venezuela in applying the methodology, but funding for this project is still pending.

A primary component in developing useful energy scenarios is the availability and quality of data. Dependable information regarding resources, technologies, and infrastructural issues is not abundant, particularly for developing countries. Future work will be significantly impacted by the availability of data for the country/region studied.

This methodology is not limited to assessing RETs or technologies that effect a reduction in carbon emissions. It could be adapted to other environmental problems (e.g., acid rain or ozone precursor air pollutants). Work currently under way at UNAM is directed at expanding the STAIR model to account for environmental factors other than carbon emissions. Furthermore, this methodology evaluates technology penetration in the energy sector on a broad basis and focuses on evaluating and comparing criteria that affect that penetration. Hence, this general methodology could be used to address problems other than carbon emissions reductions, such as labor-energy issues, reductions in fuel-use, and broad-based energy-related problems.

The deployment of RETs is one of many alternatives for carbon emissions reductions. An important task for the future is to develop a comparative analysis framework for evaluating different alternative carbon reduction strategies. This methodology could be expanded to evaluate alternative carbon reduction strategies. In addition, this methodology is modular to the extent that specific steps could be modified and still be included in the overall methodology. For example, a market model for technology penetration could be used in this methodology to give a more detailed estimate of technology deployment. (The reason that we did not use a more detailed market model was that Mexican energy data for such a model were not available, and our intention was to develop a simplified methodology.)

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Appendix A

Analytical Hierarchy Process

Analytical Hierarchy Process

After reduction of the technology list, a decision analysis tool called the Analytical Hierarchy Process (AHP) was used to further characterize the technologies in a more rigorous manner. The AHP is based on the work of Saaty [Saaty 1980], who established an analytical hierarchy for problem solving. The hierarchy breaks down the constituents of a problem into parts, and these parts are then compared with one another. Pairwise comparisons of the different elements of the hierarchy allow one to calculate the weights, or priorities, of the different elements in the hierarchy; the final results are overall priorities that evaluate the alternative solutions to the problem being examined.

The AHP has found widespread use for a variety of decision analysis applications, including recent energy analysis projects. For example, Hámalainen used the AHP to evaluate the role of nuclear energy for energy policy options in Finland [Hamalainen 1990; Hamalainen 1991]. Tzeng et al. recently used a version of the process to evaluate energy options in Taiwan [Tzeng et al. 1992].

Because the AHP can be designed to use both quantitative and qualitative inputs, it is flexible enough to incorporate specific data (such as technical or economic information) as well as more subjective factors (such as assessments of the social acceptance of energy technologies). In addition, the method of pairwise comparisons used as part of the AHP makes the analysis more manageable. Because the analyst is interested only in *relative* comparisons of a specific criterion, detailed data are not necessary for credible results; therefore, the data requirements are lessened.

As used here, the AHP hierarchy consists of three levels, as shown in Figure A-1. Pairwise comparisons of elements in the second level of the hierarchy are made with respect to the overall objective of the problem, which is given in the first level of the hierarchy. The process of comparing elements in each level is continued throughout the hierarchy (i.e., between level two and three). From these pairwise comparisons, matrices containing the priorities of different combinations of comparisons are generated. These matrices evaluate the impact of a set of elements on an element in the next highest level of the hierarchy. A general overview of the hierarchical structure of the problem using only generic technologies (more than four technologies are evaluated in the analysis) is shown in Figure A-1. The elements in the hierarchy are described below.

The first step in the AHP is the structuring of the problem into hierarchies. For our problem, the first priority (i.e., level one of the hierarchy) is to select the RETs that could best satisfy the future energy demand of Mexico and thereby contribute to large reductions in carbon emissions. RETs that have the potential to satisfy energy demands in the year 2025 are examined, although near-to mid-term factors are important (e.g., midterm cost estimates) because technologies that would reach significant levels of deployment in 2025 would have to start penetrating the energy market well before that time. In addition, our project seeks to identify technologies that are close to cost competitiveness and that would benefit from near-term demonstration projects as a means of introducing them into the market.

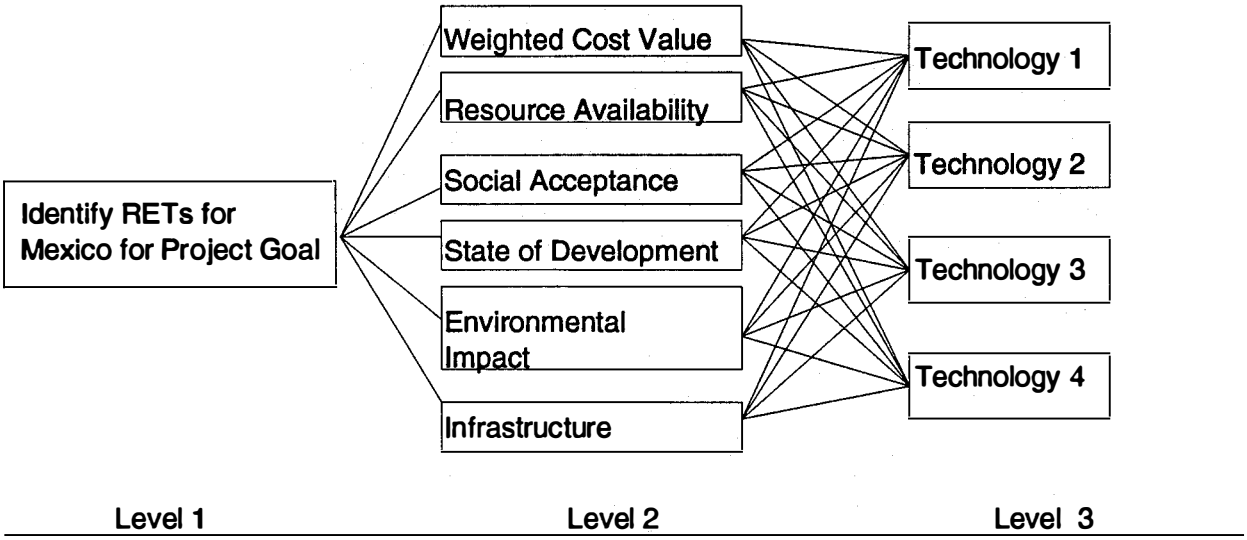

Figure A-1. Hierarchical structure of problem

In the second level of the hierarchy, the most important criteria affecting the selection of RETs *for the objective of this analysis* are chosen. The following are the second-level criteria: weighted cost value (combining life-cycle and capital costs for a technology); resource availability; social acceptance; state of technology development; environmental impact; and infrastructure requirements (see Figure A-1). The technology identification process constructed here is flexible enough to facilitate alternative analyses; an analysis with a different goal could use similar criteria, but the priorities would be different.

Categories for Analysis

The application of technologies across energy end-use sectors is not evaluated in the AHP analysis. Instead, two different end-use sectors, or categories, are evaluated–on-grid electricity and transportation–and the AHP analysis is conducted for specific technology/end-use combinations. Although the same level-two criteria (shown in Figure A-1) are used for each end-use category, a separate AHP analysis was conducted for each category because the priorities were different. For example, social acceptance was given a higher priority for the transportation category than for the on-grid category (mainly because of the requirements of the end-user to interface with the energy service). Figure A-2 shows the priorities for the second-level criteria for the two categories.

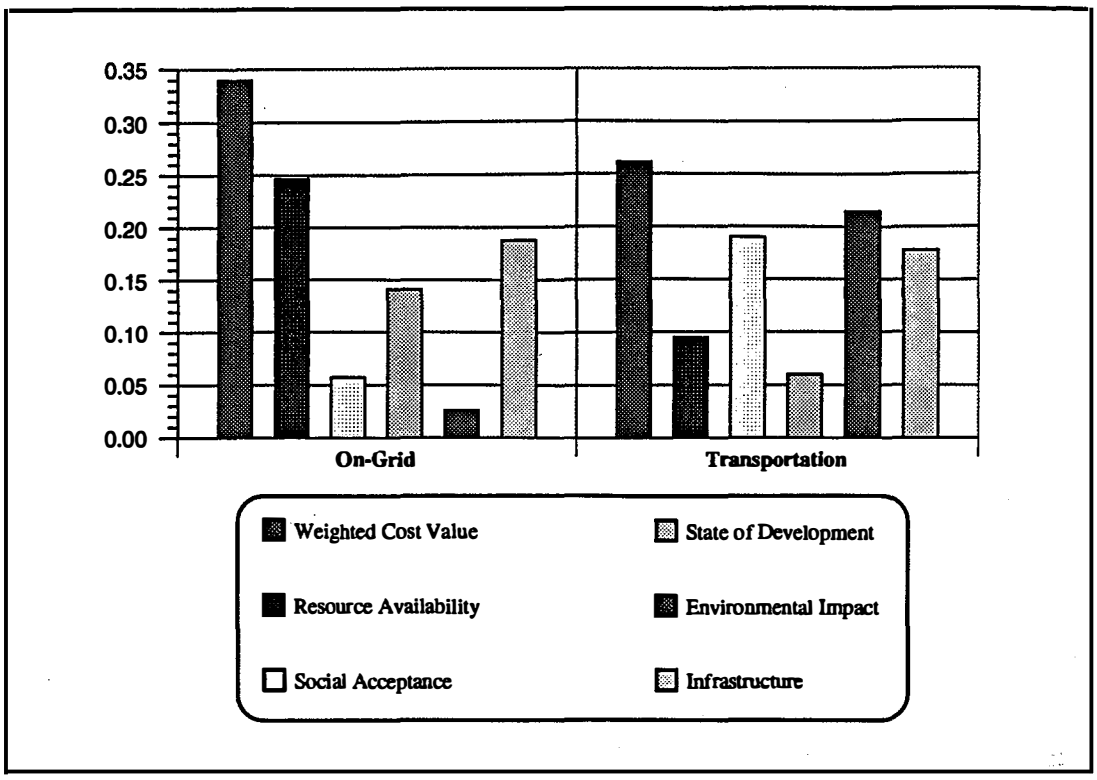

Figure A-2. Priorities for Second Level Criteria

Technologies Selected for Further Analysis

The last step in the AHP is to apply the principle of composite priorities. To establish the composite or overall priorities for the RETs, the local priority vectors resulting from the pairwise comparisons of level two and level three were combined using matrix multiplication. The results are shown in Figures A-3 and A-4 for the on-grid and transportation categories, respectively.

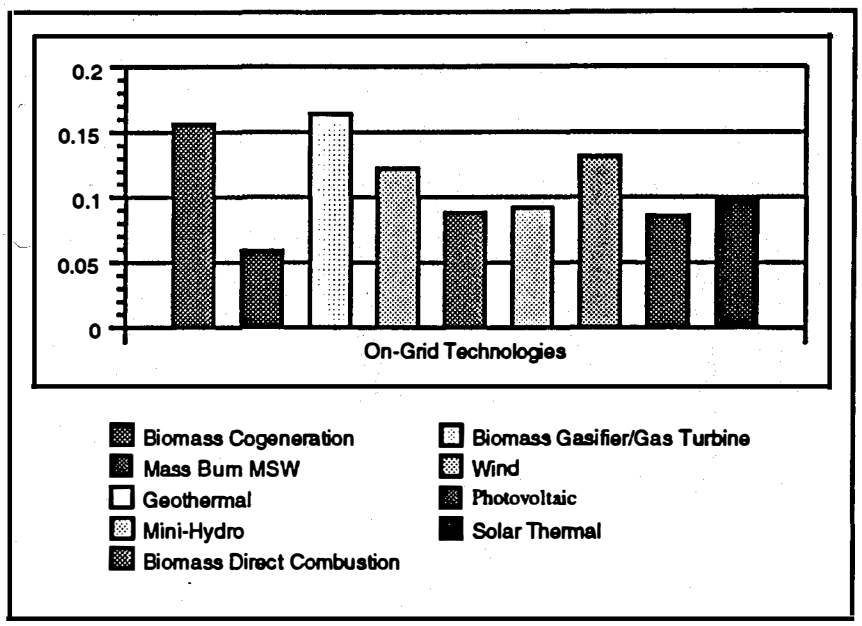

Figure A-3. Composite priorities for on-grid technologies

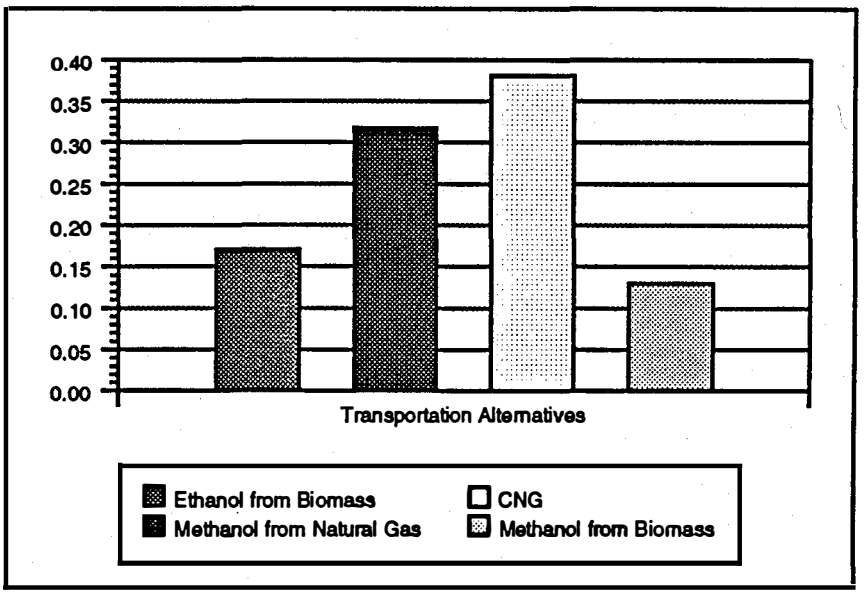

Figure A-4. Composite priorities for transportation technologies

Appendix B

Weighted Cost Value

Weighted Cost Value

As part of the AHP, a weighted cost value is used to investigate several key economic parameters. The weighted cost value takes four cost parameters--current, midterm (year 2010), and future (year 2025) life cycle costs, and near-term (year 2000) capital costs--and combines them, along with a series of weighting factors, in a linear equation that provides a single number for each technology (called the weighted cost value).

The use of the weighted cost value as an input to the AHP allows quantitative indicators of technology characteristics to be included in the subjective decision-making process represented by the AHP. By combining multiple technology parameters into one value, several characteristics can be considered without complicating the AHP by adding too many parameters.

The weighted cost value is calculated as follows:

$$OFV = a*(RC/LCC)_{present} + b*(RC/LCC)_{2010} + c*(RC/LCC)_{2020} + d*(RC/CC)_{2000}$$

where,

OFV = weighted cost value
LCC = life-cycle cost in the year indicated
RC = reference cost in the year indicated
CC = capital cost in the year 2000
a-d = weighting coefficients (a+b+c+d = 1.0)

The life-cycle cost for each technology was determined from the literature [OTA 1992; SERI 1990; SERI 1990a; EPRI 1986; SAIC 1990; DOE 1992]. Weights given to each parameter of the weighted cost value depend upon the intent of the analysis. For example, an analysis focusing on near-term economic viability would emphasize near-term life-cycle costs. It is therefore important in explaining the set of chosen weighting factors to discuss how each parameter relates to the overall goal of identifying RETs that have the potential for significant deployment by 2025 and that would therefore result in large carbon emissions reductions.

Although life cycle cost estimates inherently include capital costs, capital costs (c. 2000) have been included as a separate technology parameter in the weighted cost. The up-front capital outlays for a project, especially in a developing country such as Mexico where capital for large-scale energy projects can be scarce and the government's foreign debt is extremely high, are an important part of the overall investment criterion for a project. The capital costs ($/kWh) used in the weighted cost value are based on a typical size project for the given technology.

The following weighting factors were used in this analysis: year 2000 capital cost - 0.15; present life-cycle cost-0.20; 2010 life cycle cost-0.55; and 2025 life cycle cost-0.10. The weighting factors emphasize mid-term costs (i.e., c. 2000-2010). Although technology penetration curves are not evaluated (e.g., logistic curve representation for technology penetration over time), it is assumed that technology deployment would have to start in the near-or mid-term if a significant penetration were to occur by 2025, and the weighting factors reflect this. Mid-term costs are also emphasized because a by-product of this study is to identify near-term demonstration projects for promising technologies. These projects do not

currently have to be cost competitive, but they should be cost competitive in the midterm (i.e., about 2000-2010). Of course, technologies that are already mature (e.g., geothermal) could start to penetrate the market in the near-term; hence near-term costs are weighted accordingly. Finally, 2020 costs were given the least emphasis because they will have less impact on mid-term technology deployment and because of the high uncertainty associated with these estimates; however, they are important for indicating the long-term potential for technological improvements.

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 1994	technical report

4. TITLE AND SUBTITLE
Renewable Energy and Its Potential for Carbon Emissions Reductions in Developing Countries: Methodology for Technology Evaluation--Case Study Application to Mexico

5. FUNDING NUMBERS
WF945440

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
TP-463-6504

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Environmental Protection Agency
401 M Street, SW
Washington, DC 20460

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE
UC 1321

13. ABSTRACT *(Maximum 200 words)*
This report describes a study of a method to identify renewable energy technologies that have the potential to reduce carbon emissions while meeting key criteria for commercialization and acceptability in developing countries. In addition, this study evaluates the connection between identifying technologies that have the potential to reduce carbon emissions and selecting projects designed to demonstrate those technologies. The study used Mexico as a case study, but the methodology is broad based enough to be applied to other developing countries and to other technologies. The evaluation method consists of four steps: screening, identifying, creating deployment scenarios, and estimating carbon emissions reductions. Both on-grid and transportation technologies (including CNG) were analyzed. The method could be used to help formulate long-range energy plans for RETs, taking into account both carbon emission reduction potential and economic viability. It could also be adapted to evaluate other environmental and energy-related issues.

14. SUBJECT TERMS
carbon emissions reductions; evaluation methods; developing countries; Mexico

15. NUMBER OF PAGES
48

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified	unclassified	UL