

Assessing the potential and costs of reducing energy demand

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Abstract Determining the cost of energy saving measures and the magnitude of their potential application is the first and essential step to correctly design energy efficiency policies, which are in turn a keystone for energy transitions. This is particularly relevant for MENA countries, which feature energy intensities among the highest in the world. This paper presents a methodology for assessing reductions in energy demand based on expert evaluations; the methodology incorporates several improvements over previous similar studies. Our results suggest a significant potential for energy savings, and recommend different policy designs based on the different costs and potentials of different energy saving measures.

Keywords Energy demand · Energy efficiency · Marginal abatement curves

Introduction

Energy efficiency and energy conservation remain central pillars of energy policy, particularly when considering the need in many countries for an energy transition towards decarbonization. Energy savings would allow for achieving at the same time the major goals of an energy transition: cost minimization, security of supply, and environmental

sustainability. This is highlighted in several documents of many international institutions (e.g., [11, 16]).

The benefits of pursuing energy savings are confirmed by most of the literature on energy efficiency. For example, Bernstein et al. [4] show that the 1995 GDP of California would have been 3% lower if significant measures to improve energy efficiency had not been implemented from 1977 to 1995. Wesselink et al. [26], p 16 argue that improvements in energy efficiency create employment. Moreover, at the firm level, energy efficiency improvements benefit the firm's reputation and brand value because consumers are increasingly becoming environmentally conscious (see for example [13] or [2]).

These facts explain the commitment of many countries and regions to improve their energy efficiency. For example, the EU has set its target to 20% by 2020 [10]. However, some countries are still behind in this aspect, and still focus their analysis of energy transitions almost solely on energy supply, not on energy demand. To look at the bright side, this on the other hand means that there is still a large potential, particularly in the residential and commercial sectors.

In the case of MENA countries, this may be even more relevant: according to Duro [7], energy intensity in the Middle East and Africa has increased in the last years, and is among the highest in the world, therefore pointing to a large potential for energy demand reductions and its related benefits. Therefore, it seems particularly timely to bring this topic to the top of the political agenda, and to elaborate plans to address it.

One pivotal element for the design of such plans is the correct evaluation of the available potential to reduce energy consumption and the related costs. In this regard, many studies have found that energy savings and energy efficiency measures are rather cheap, and might even come at negative costs. This would mean that the implementation of such measures also produces economic net gains. This is

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for example the most salient aspect of the studies by McKinsey [9, 20]. However, if so many measures exist that yield a net economic benefit, why are they not implemented spontaneously (without the need of policy support)? This is known as the paradox of energy efficiency: the fact that apparently beneficial measures are not put into practice. The issue has been discussed in the scientific literature (see for example [2, 19]; or [6]). One of the possible explanations for the energy efficiency paradox is that many studies underestimate the real implementation cost of energy efficiency measures, for example by not considering hidden costs or risk premiums. Another prominent reason is the requirement of higher rates of return by private investors (which in turn relates to several other possible problems).

Not considering these higher costs usually leads to overestimating the energy saving potential from an economic point of view; and to underestimating the cost of implementing energy efficiency policies. Another problem regarding the correct evaluation of the implementation cost of energy efficiency measures is the existence of interactions between different measures, which are often not considered: some energy efficiency measures do overlap. For example, investing in home insulation makes less sense once a more efficient boiler has been installed, since that reduces the amount of energy that can be saved with insulation. This leads to a total energy demand reduction potential which is smaller than the mere sum of individual measures. Again, this leads to an overestimation of the saving potential and an underestimation of implementation costs. Finally, it is important to distinguish between energy efficiency and energy saving measures. It is possible that improvements in efficiency do not translate into energy savings due to the rebound effect.¹ Several mechanisms exist that can minimize the rebound effect, but its effect should still be always taken into account.

Either way, only if we evaluate reduction potentials and costs correctly we will be able to decide which part should energy efficiency play in energy policies, and how to design energy policies efficiently. Hence, improving the quality of the assessments of energy reduction potentials and implementation costs is paramount for the design of an efficient energy transition. In this paper, we present a rigorous estimation of the energy reduction potential and the associated costs from a consumer perspective.² In this way, it is possible to understand until

¹ In section “Challenges regarding the estimation of reduction potentials and costs” we explain this effect in more detail.

² Note that for policy evaluation purposes the social cost is the appropriate measure. But for policy design it can be preferable to use the evaluation from the private perspective, since it will provide a better indication of the potential degree of adoption of the policy.

what point energy efficiency and saving measures should receive policy support, how support policies should look like, and which sectors to focus on to achieve the goals set in the best possible way.

How to assess the costs and reduction potentials of energy saving measures

A very appealing method to represent the economic costs and the potential of different energy saving measures is a marginal abatement cost curve. Such a curve provides the information to compare the costs and benefits of different saving options, thereby being a valuable tool for decision-making. This methodology is related to earlier efforts to evaluate CO₂ emissions reductions. A wide range of literature exists already for the assessment of CO₂ reductions, while efforts to apply it to energy savings are very scarce.

Producing marginal abatement cost curves

Baker et al. [3] define the marginal abatement cost curve (MACC) as the deviation from an alternative scenario. Jackson [17], who calculated one of the first MACCs for CO₂ emissions, defined his curve similarly: “The savings curve then provides a direct comparison of the different abatement options in terms of their relative cost-effectiveness and their potential for reducing CO₂ emissions.” This quote from Jackson [17], p 35 highlights the goal of marginal abatement costs curves, which is to identify those measures which provide CO₂ reductions at lowest cost. Clearly, this principle can be extrapolated to energy savings, and thus is the one we follow in the paper.

The alternative scenario (the baseline or business as usual one) would be the situation in which we model the behavior of industries and consumers without reduction policies. The MACC approach would, thus, provide information on the reduction potentials and costs of reduction measures beyond the baseline scenario.

Figure 1 depicts a marginal abatement cost curve for energy demand reductions. Blocks 1–8 represent individual energy saving measures. The *x* axis shows the potential for reductions, e.g., in MWh, whereas the *y* axis shows the specific, marginal cost, of each MWh reduced (e.g., in €/MWh). Thus, the curve represents the different potentials and costs of measures in a convenient and clear way. It facilitates the identification of how much it costs to save one additional energy unit, or the actual saving potential for a certain price (the current energy price, for example). The curve also allows for calculating the total costs of a given desired reduction, which is equal to its integral (the area below the curve).

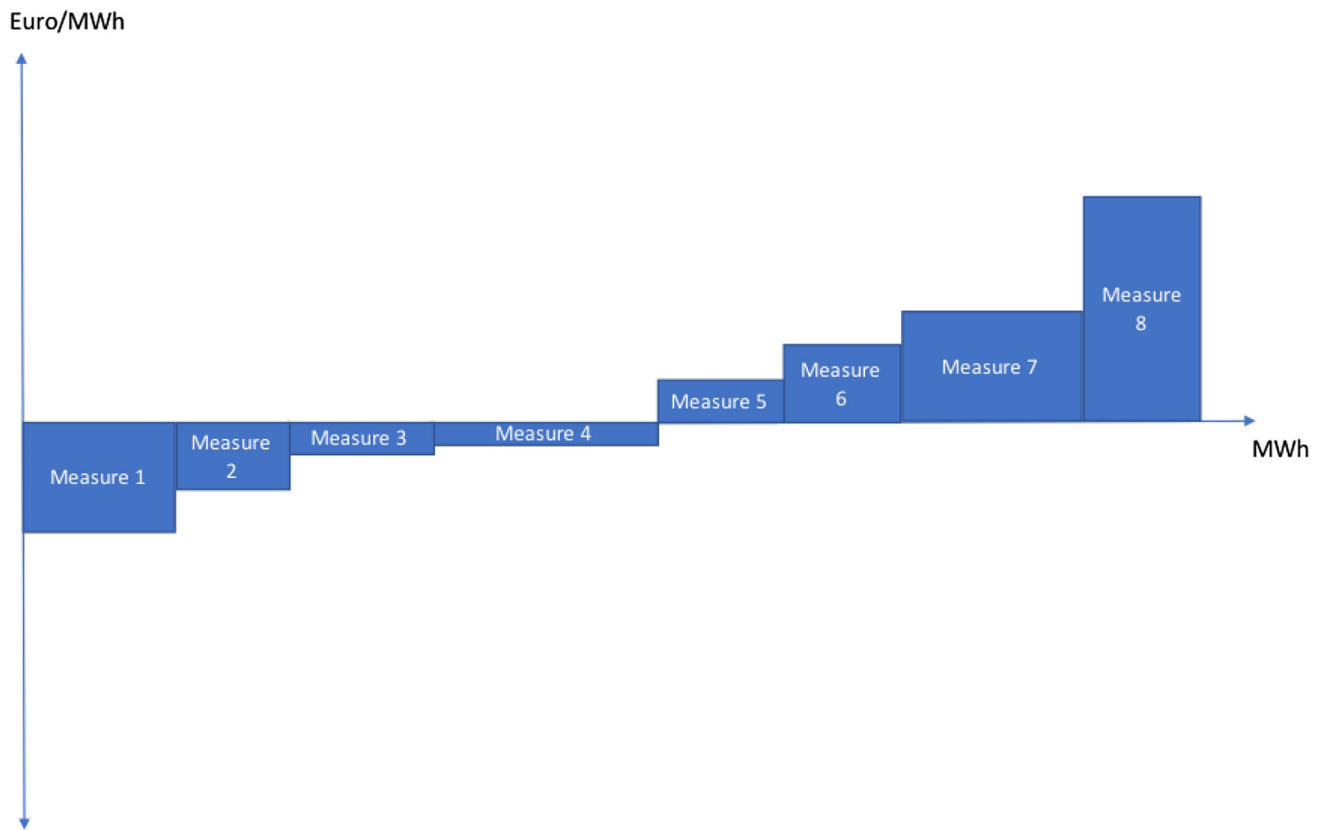


Fig. 1 A marginal reduction cost curve for energy savings Source: the authors

Methodologies to calculate marginal abatement cost curves

Marginal abatement cost curves (or marginal reduction cost curves for the case of energy demand reductions) can be calculated in several ways: relying on the information provided by experts (expert-based), or on models (model-based). Figure 2 presents the different options to generate marginal energy reduction cost curves.

Expert-based curves

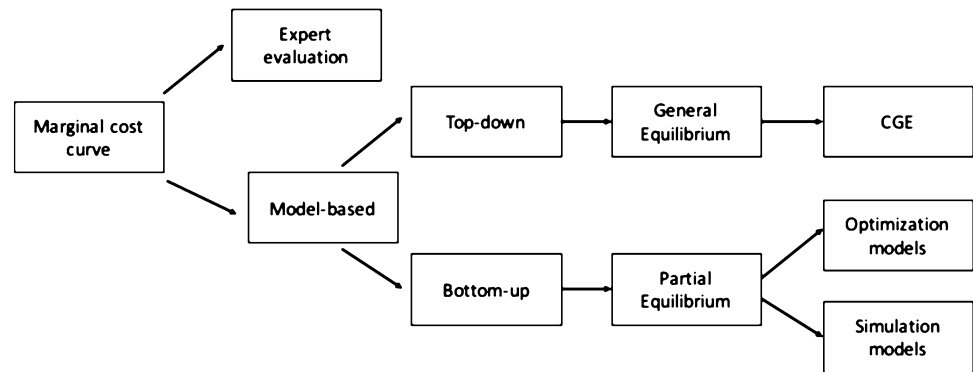
Expert-based curves were first used in the 1970s to estimate the reduction of electricity and petrol use [18]. Currently, the most renowned expert-based curves are those generated by Bloomberg New Energy Finance [23] and McKinsey and Company [20]. These curves rely on detailed expert insight about individual saving measures. Hence, each reduction measure is analyzed individually, which benefits precision on one hand, but at the same time increases the risk of not including interaction effects between measures. Expert-based curves often over-estimate reduction potentials for that reason.

Model-based curves

Model-based curves, on the other hand, rely on the modeling of the energy sector or the economy as a whole. The model allows to quantify the current or future production, emissions and/or energy consumption accurately.

A marginal reduction cost curve based on a model relies on the correct representation of economic reality within either a general equilibrium model for the entire economy or a partial equilibrium model of the energy sector. Usually, models cannot consider technical details in the same way as expert-based methods can. Models are also less transparent regarding the assumptions made. Moreover, it is difficult to take specific problems of the energy sector into account (irrational behavior, market imperfections, complex barriers which are difficult to quantify). However, models allow for including feedback effects on the economy as a whole, and they can consider interactions between certain measures. Also, models define the market penetration of the measures endogenously. Model-based methods usually calculate several scenarios restricting quantities or prices to certain thresholds. The new scenario with a constraint on energy prices or emission levels then provides information on the consequences and economic

Fig. 2 Methodologies to calculate marginal reduction cost curves Source: the authors



costs of achieving a new situation under these constraints. Model-based methods can be divided into different categories:

Bottom-up model-based curves Bottom-up model-based curves use a partial equilibrium model of the energy sector. A wide range of technologies in the energy sector can be considered, to estimate the substitution possibilities between energy types, processes, and the energy efficiency improvements. The effects on the energy sector are either simulated mathematically or through optimization (cost minimization or profit maximization). In this way, the model yields the least cost energy system for a certain energy demand given the restrictions concerning available technologies and implemented energy policies. Bottom-up models have been used to estimate marginal reduction costs or energy demand reduction curves occasionally. One example is the TIMER model (Targets Image Energy Regional) developed by the Dutch National Institute for Public Health and the Environment. It is a dynamic model which considers inertia, fossil fuel depletion, and inter-regional trade. Another example is the PRIMES model, which is used by the European Union to assess the consequences of climate and energy policies. The PRIMES model was for example used as a basis for a CO₂ emission reduction cost study for the European Union (see [25]. Wesselink et al. [26] apply the same technique to estimate a marginal cost curve of energy demand reduction for the EU area. Charlín and Watts [5] apply a similar approach to generate a marginal saving cost curve for the Chilean energy sector. Moreover, several adaptations and recalculations are made within the time frame until 2030 to take account of secondary effects and interdependencies between sectors. A curve for Spain was developed by Santamaría et al. [21] for CO₂ emissions in the industrial sector, concretely for the steel, cement and electricity generation industries. The authors construct bottom-up models for each sector and estimate the impacts of incremental constraints regarding CO₂ emissions. In this case, the model optimizes the use of the mitigation options.

IDAE [15] also estimated the potential to save energy consumption in Spain with help of the MURE model (Mesures d'Utilisation Rationnelle de l'Énergie). The prime objective of the study was to estimate aggregate potentials, not the costs and potentials of individual technologies. Hence, the study does report an energy saving potential for Spain, but it does not provide a marginal energy savings curve.

Top-down model-based curves The energy sector typically plays a crucial role within the economy. For a marginal reduction cost curve with an energy perspective the study of the effects of changes in the energy sector on the remaining sectors of the economy is particularly interesting. Top-down models consider the entire economy, taking account of the interactions between sectors due to market distortions, economic rents, and consequences for economic agents like families or governments. Obviously, the complex mathematical calculations necessary to represent the broad range of effects often requires a reduction of the detail of technological data input which leads to less detailed results.

Challenges regarding the estimation of reduction potentials and costs

Both approaches, expert-based and model-based, have merits and drawbacks. Choosing the most appropriate method is not easy and should be done carefully, because the results typically depend heavily on the method chosen [8, 12]. Some problems can be related to a certain methodology, others relate to the characteristics of the source data or the application of a model. In the following section we summarize the most relevant problems identified in previous estimations.

First, a thorough and well-thought definition of the baseline scenario is crucial. Some studies do not consider that some measures are already applied (already existent in regulations) or they fail to include that the economic or technological development will affect energy demand. If

these effects are not considered, the energy saving potential or CO₂ reduction potential is typically overestimated.

Market imperfections or irrational behavior by market participants are also difficult to model. Tietenberg [22] and Convery [6] evaluate and discuss these effects in more detail. For example, households may require relatively high rates of return for energy efficiency investments, which leads to lower investments in real markets than those levels predicted by models. Other reasons why apparently beneficial investments are not made by real actors can be market imperfections, market barriers, or incomplete information. Not considering these elements also yields overestimations of real saving potentials. The most striking illustration is negative cost measures, which obviously provide net economic gains, but are not implemented by real agents.

One of the most common problems of expert-based studies is the lack of consideration of the interaction between energy saving technologies. One unit of energy can only be saved once. It is then important not to overestimate the reduction potential of overlapping technologies and reduce the saving potential of each technology according to its degree of overlap with other measures. There can also be interactions between sectors. An increased use of electric vehicles in the transport sector, for example, will change electricity consumption and affect the outcomes in the electricity sector.

Another shortcoming of expert-based models is the representation of the rebound effect. The rebound effect describes an increase in energy consumption after energy efficiency improvements because the energy efficiency measures lead to lower relative energy prices. The quantification of this effect requires more complex general equilibrium calculus. Yet, the size of a rebound effect depends on the individual energy efficiency instrument, so it cannot be estimated in a general way.

We should also mention the difficulty of incorporating the effects of technological progress. Marginal reduction costs studies in general make predictions about the medium-term with considerable uncertainties regarding the development of individual technologies, their costs and fuel prices. This is an unresolved question; the most attractive remedy is transparency concerning the assumptions of the model, and to evaluate the sensitivity of the results against these assumptions.

Finally, probably the biggest problem is the unavailability of reliable data like actual consumption (to establish the baseline scenario), technology costs, etc. This is possibly the most relevant limitation for research projects of this kind, especially in many countries. It is not possible to solve this by methodological adjustments.

Due to these potential pitfalls, a marginal reduction cost curve should be constructed very carefully. We took a wide

set of measures to reduce the possible biases related to the previously described limitations in this paper. These measures are described in Sect. 3.

Methodology

In this section, we describe the analytical framework followed, and the measures taken to tackle the previously described difficulties and limitations. We follow an expert-based approach with several modifications. We rely on expert opinions for the determination of market penetrations for the different energy saving technologies for the different scenarios. This provides very detailed information on individual technologies: we include between 15 and 50 possible energy saving measures for each sector and define costs (investment, maintenance, operation, and fuel cost), and energy intensity for each of the measures. For energy intensity we distinguish between electrical and thermal energy intensity, to be able to assess the consequences of saving measures in the electricity sector. In the end, both intensities add up to a common energy scale by means of the efficiency factor in the electricity sector.

Our analytical framework features the following characteristics and modification compared to previous approaches:

- We calculate the long-run marginal costs of each energy saving technology. These long-run marginal costs are the sum of the operation, maintenance and fuel costs and the initial investment expenses, the latter of which are annualized by means of a discount rate which can depend on the scenario used (the scenarios are described in the following section).
- Then we identify the counterfactual scenario. For example, we assume that gas condensing boilers substitute traditional gas boilers, or more efficient diesel cars substitute older diesel cars. In some cases, the counterfactual cannot be identified clearly. We then take the sector average as a reference (this is done in the electricity sector, for example, since it is difficult to define the one single technology replaced when certain newer, more efficient technologies are installed).
- Once the reference technology is identified we calculate the difference between the long-run marginal cost of the new and the reference technology, which yields the economic cost of an individual energy saving measure.
- The energy saving potential is calculated likewise, as the difference between the energy intensity of the new and the reference technologies, which is then multiplied by the market penetration (as the difference between the market penetration value of the new technology in

the baseline compared to the new scenario). Penetration (or implementation) values are determined externally by expert judgement.

- We divide the cost of a certain measure by the achieved energy savings, which in turn gives the costs per MWh saved. This allows us to rank the energy saving measures according to their costs (from attractive to unattractive from an economic point of view).

At the end of these steps, all necessary values to construct one block of the marginal energy saving cost curve are obtained. Figure 3 illustrates this.

Our framework is also capable of solving some of the typical limitations of previous approaches. We consider two possible evaluations of energy reduction potential and cost, one under the public or social perspective, another from the private point of view.

The difference between the two perspectives is the following: the public evaluation looks at this issue from a social or public administration point of view. Therefore, we look at prices before taxes (since we must assume neutrality in the tax revenue). The social evaluation also uses one coherent, social discount rate for all measures.

In the private evaluation, on the other hand, we use final prices including taxes and different discount rates to represent real decision-making in different sectors appropriately. In the industrial sector we use 9%, in the residential sector we use 30%, and private transportation 20%. This flexibility of discount rates represents the fact that households and private decision-makers sometimes require unusually high discount rates to implement energy efficiency measures (see for example Hausman [14] or Allcott and Wozny [1]).

As mentioned previously, we only represent the results of the private point of view in this paper, since this perspective is better suited for policy design, as it represents better the decision-making process of private investors.

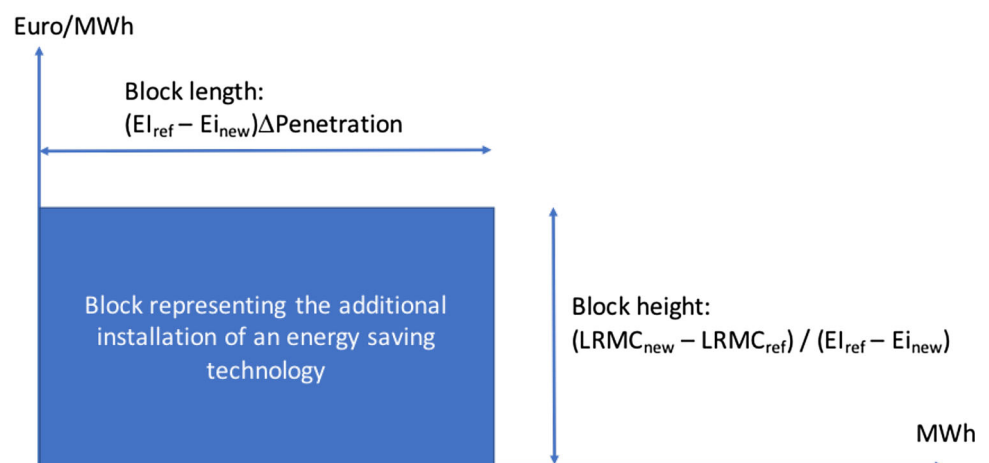
Not all market imperfections and barriers can be modelled by adjusting the discount rate. Other imperfections are considered by adjusting the market penetration rate, taking account of a certain difference in the real penetration value vs the one calculated with pure cost figures. At the same time, we also explicitly adjust the original costs of certain measures to reflect additional transaction or information costs.

The interaction between technologies is accounted for as well. To do so we first define which technologies present overlaps (for example home insulation and advanced heating systems, or electricity saving measures and technologies in the electricity sector). We then correct the saving potential and the cost of these technologies by a sequential pattern, by looking at which technologies enter before others based on costs. For example, electricity saving technologies, if implemented first, affect the potential gains of energy savings in the electricity sector, which then affects the costs per MWh saved there.

Other effects that cannot be accounted for by the adjustments described above can still lead to negative cost technologies, meaning that there may be measures which are highly beneficial in economic terms but are not implemented by real decision-makers. In this regard, we should clearly acknowledge that our model is not able to account for effects or barriers other than those described above. For these cases, however, we believe that our model is useful to identify remaining market inefficiencies, displaying clearly where policy interventions are desirable to correct this.

Of course, the precautions and adjustments made cannot account for the numerous uncertainties in real markets (like the definition of technologies and most of all their market penetration). These uncertainties are reflected, at least partially, in the different scenarios modelled. These scenarios are described in the following section.

Fig. 3 Construction of the blocks of the marginal energy saving cost curve Source: the authors



Scenarios and measures considered

We now introduce the data used for our study. Technological and economic data for all energy efficiency measures come from Bloomberg New Energy Finance, which kindly gave us access to their proprietary database. These data are global in nature, not country specific, so our results can be easily applied to many countries, in particular those in the MENA region.

What is more country specific is the level of energy demand, and its distribution among sectors, as well as the fuel mix. For this we used Spanish data, although again this is not that critical: as we can see in the following table, the Spanish energy sector is not that different from the one in MENA countries, in terms of structure of final demand (and therefore of the relative weight of energy efficiency measures) (Table 1).

Also, we can compare the primary energy consumption of Spain with those of some countries in the MENA region, as shown in Table 2.

Therefore, we think that our results and scenarios are easily applicable to the study of energy transitions in the MENA region. But even for those countries in which the energy sector structure is very different, results can be applied on a technology-specific basis: given that the costs and energy intensities are taken from an international database, the individual cost of each energy efficiency measure can be used directly, while the potential for energy reduction depends on the penetration chosen by the analyst.

Given that the objective of this study is to increase the quality of the available information for policy-making, and that climate change and environmental policy are long-term issues, we have set the horizon for the study in 2030. Therefore, the results we present estimate the possible energy savings and costs in that date. We present two scenarios, a political and a technological one (see Table 3). In these scenarios, we compare the possible outcomes of certain changes relevant for energy saving efforts in comparison to the baseline, where the baseline represents those advances and efforts already foreseeable today.

Thus the baseline already incorporates those changes and energy savings that can be achieved when no additional action beyond the existing and definitely planned

measures is taken. It already includes those renewable plans or energy efficiency policies already determined and foreseen within the 2030 horizon in Europe. Of course, this scenario might need to be revised if applied to a MENA country, for which the level of ambition of current energy efficiency policies may vary. Again, it should be noted that this only affects the penetration of the different measures, not their expected costs or energy intensities.

Comparing the situation of 2010 with the one of 2030 under the determined and predicted advances and policies, the baseline scenario evaluates the savings that should be taken for granted. The detailed composition of such a baseline scenario is a major improvement relative to earlier marginal reduction cost curves in which it was not that clear whether the savings were measured against this future baseline or against the current situation.

The two additional scenarios (political and technological) attempt to capture the uncertainties about the path to 2030: technological progress, market penetrations, technology costs, etc., and also the different policies that could be pursued.

The technological scenario considers increased penetrations of certain technologies (for example solar photovoltaics in electricity generation, high efficiency boilers in heating, electric cars) associated to possible cost reductions for these technologies until 2030. This scenario also assumes, in order to be internally consistent, lower natural gas prices which result from technological improvements in the natural gas supply chain. This scenario will probably require political support, but oriented towards technological development and not so much towards technology adoption.

On the other hand, the political scenario does not include cost changes. It is meant to represent political efforts to promote the most energy-efficient technologies without considering their costs.

A complete list of all costs and penetrations assumed for the scenarios is available as supplementary material. The technologies considered are also listed and described.

The following sectors are included in our analysis: residential buildings, commercial buildings, transport (public, private, road, rail), and the electricity generation sector. We also include the following industrial sectors: aluminum, ammonia, bricks, cement, steel, ceramics, petrochemical industry, and oil refining. The sectors included represent 81% of Spanish energy demand, and probably a similar share of other similar countries (see Table 1).

It is important to note that we only consider technological measures, not behavioral changes: for example, we consider changing the type of vehicle, not a reduction of average speeds on roads, efficient driving or a change in mobility demand. We thus limit the analysis to such measures whose effects can be estimated reliably.

Table 1 Relative weight of different sectors in final energy consumption [16]

	Middle East (%)	Africa (%)	Spain (%)
Industry	26	17	28
Transport	29	17	39
Buildings	28	62	30
Other	17	4	3

Table 2 Primary energy and electricity consumption in Spain and selected MENA countries in 2014 [16]

	Primary energy demand (Mtoe)	Electricity consumption (TWh)
Spain	115	249
Algeria	52	53
Egypt	75	152
United Arab Emirates	70	102
Saudi Arabia	213	291

Table 3 Description of scenarios

Scenario	Description
Baseline	Estimates the penetration of technologies envisaged by the current policies or those already expected to enter into force before 2030. Costs are taken from the Bloomberg New Energy Finance database. Energy demand reductions are calculated against the energy demand in 2010
Political	Increases the penetration of energy-efficient technologies compared to the Baseline scenario, according to the best judgment of the experts. Costs of technologies are the same as in the baseline scenario. Energy demand reductions are calculated against the energy demand for the baseline scenario in 2030
Technological	Increases the penetration of some technologies (those with the largest potential for improvement, according to the experts), but not for others, which become less competitive because of an also assumed decrease in natural gas prices. The costs of these innovative technologies are also reduced based on the experts' opinions. Energy demand reductions are calculated against the energy demand for the baseline scenario in 2030

Behavioral changes, although very interesting and potentially highly effective, are excluded solely because the costs of the various tools to achieve them are very difficult to estimate: Advertising and awareness programs, price incentives, prohibitions, etc. All these tools incur administrative costs and welfare reductions which are hard to measure (although one could calculate them by changes in consumer surplus in some cases). Another problem when integrating these measures would arise when defining the reaction of consumers to these programs and thus the reduction potential. Anyway, these behavioral changes could always be included ex-post.

Results

In this section, we present the results for our three scenarios: the baseline, the technological scenario, and the political scenario. Note that we only report the results from the private point of view in this paper.

Baseline scenario

The baseline scenario estimates the energy demand of 2030, given the expected development of the different technologies and the implementation of the predicted policies in this period, and compares it with a situation without technological changes between 2010 and 2030. The results show that energy demand in 2030 is 2% below the 2010 levels because of the efficiency gains of new

technologies; despite the growth in the demand of energy services in some sectors (buildings, transport, etc.) these more efficient technologies reduce energy demand by 26% compared to the situation in 2030 when the technological level corresponds to 2010. Hence, the already foreseeable progress of policies and technologies alone would be able to stabilize Spanish energy demand at 2010 levels despite an increase of demand of energy services. Figure 4 depicts the marginal reduction cost curve for the baseline scenario.

The technologies that contribute most to energy reductions are wind and solar energy in the generation sector, and measures in the transportation sector like hybrid cars, more efficient trucks and trains, and the switch from road to rail. Significant energy savings are also identified for heat pumps, efficient gas boilers, and more efficient fuel vehicles, allowing for a large reduction of demand at negative costs.

The aggregate cost of energy demand reduction is not nil, but not large: 73% of the total savings (26% compared to the situation with frozen 2010 technologies) is achieved at zero or negative costs. And 84% of the reduction can be achieved at a cost lower than 50€/MWh (which is also the natural gas price considered in this scenario). So the overall cost of the set of expected energy savings in this baseline scenario is negative (net gains of €4.100 million). Even when several measures are taken to represent and correct for the energy efficiency paradox, such as higher discount rates, a wide range of measures cost less than €50 per saved MWh energy. These results might suggest that there are still non-considered or hidden costs, transaction costs or

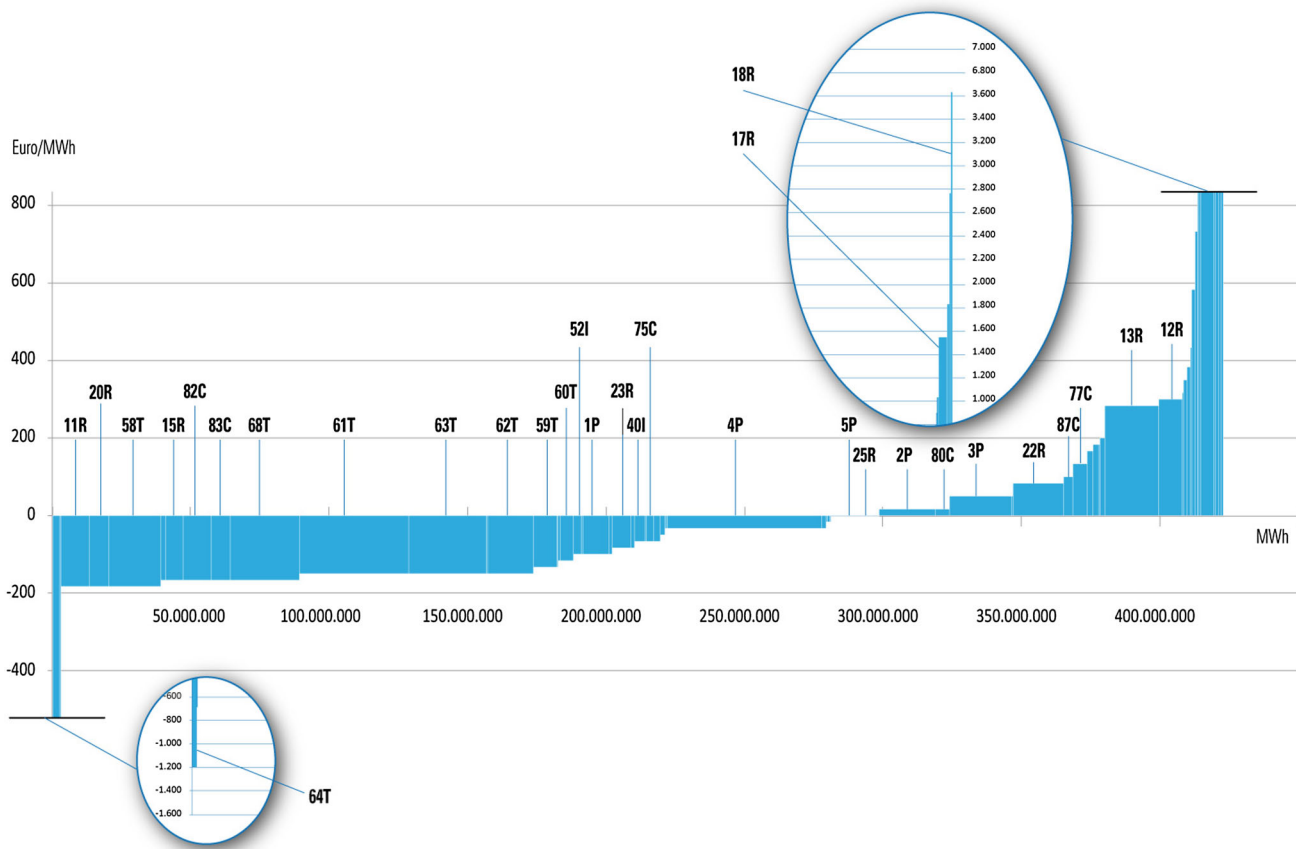


Fig. 4 Energy savings potential for Spain 2010–2030 (baseline scenario). Note: consult the appendix for the identification key of individual measures along the curve Source: the authors

barriers that prevent the adoption of economically efficient measures.

Also, the high cost of some technologies casts doubts on their cost-effectiveness, for example the geothermal heat pump and home insulation (despite their large reduction potential) and some efficient appliances.

Regarding the insulation measures, we should highlight that we consider only retrofits for the sole purpose of energy efficiency. If such retrofits are integrated in other necessary renovation works (accessibility, other requirements), or when insulation measures are included in new construction, the costs will be much lower. Therefore, the pay-off of insulation in our model is an upper limit for the case of a retrofit. It is potentially much lower for new buildings or if the works are coupled to other necessary renovations.

For the other two scenarios, the counterfactual is no more the 2010 situation but the 2030 baseline. These scenarios, the technological and political scenario, represent situations where additional efforts are taken beyond what we expect to happen anyway until 2030.

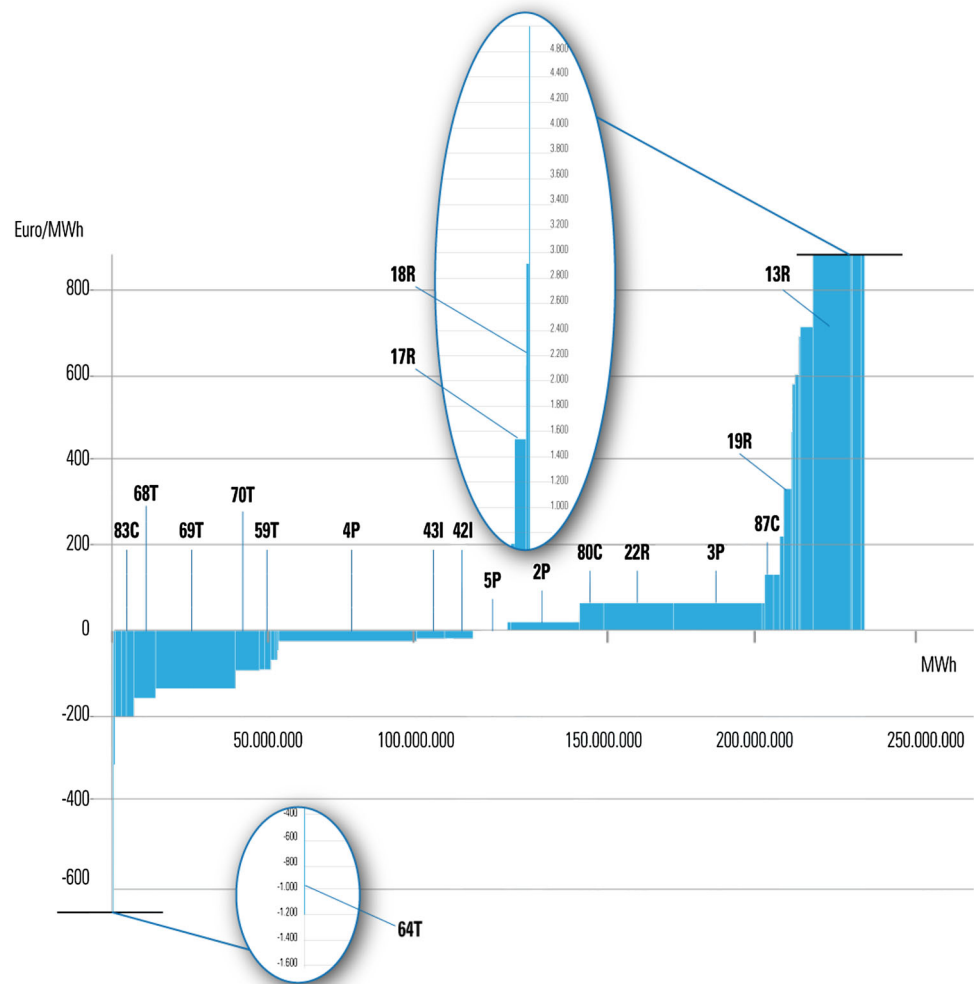
The political scenario is a very ambitious one, because it yields energy savings of 19% versus the baseline scenario.

The marginal costs of the reduction are higher than in the previous scenario: 50% of the reduction can be achieved at negative costs, and 60% at costs lower than 50 €/MWh. Beyond this 60%, the costs rise significantly, which indicates that the potential of reduction is limited economically. Again, the geothermal heat pump, insulation measures, and electric household appliances inflate the total costs of the achieved reductions in this scenario, which total €35.000 million. Still the total costs can be kept at zero if only measures with costs below €1.000/MWh are taken.

The increase in energy reduction costs is explained by the limited availability of cheap reduction technologies like more efficient gas boilers. The less efficient boilers were already substituted in the baseline scenario, which leaves less room for further efficiency gains. This highlights the relevance of determining correctly the baseline for this type of studies. Figure 5 depicts the marginal energy reduction cost curve for this political scenario. As may be seen, the best measure in this scenario is biodiesel trucks, followed by LED lighting, efficient trains, and changing freights to rail.

Finally, the technological scenario assumes an additional technological advance for the most efficient energy saving measures (including a reduction of the installation

Fig. 5 Energy savings potential for the political scenario, Spain 2030. Note: consult the appendix for the identification key of individual measures along the curve Source: the authors



costs). But since this scenario does not assume aggressive political regulation for energy efficiency, the assigned penetrations are generally lower than in the political scenario. Consequently, energy savings are lower than in the political scenario. They amount to 15% relative to the baseline (the political scenario yielded 19%). In this scenario some (more efficient) technologies yield bigger reductions, like LED illumination measures, hybrid and electric vehicles, and solar water heaters.

The assumptions of this scenario affect the costs of the measures in two ways. Obviously, the reduction in the installation cost of some technologies also reduces the costs of the achieved energy savings. But the economic value of saved energy also falls because of the assumed reductions of natural gas prices. Therefore, the total costs are somewhat higher than in the political scenario, even for a reduction in energy demand which is three times lower than in the political one: 43,200 million euro in the private case. In this technological scenario 42% of the reduction can be achieved at negative costs, less than for the political scenario. Again, the most expensive technologies are

insulation measures which nevertheless yield significant savings. The most interesting measures in this scenario are energy management in steel production, LED lighting in residential and commercial buildings, hybrid and electric cars, and wind energy. Figure 6 shows the costs and potentials for this scenario.

Finally, it is important to highlight the influence of the interactions between different energy saving measures. When we consider these interactions, the energy saving potential is reduced by 5–10% (depending on the scenario). In particular, the reduction potential decreases and the costs increase for the most expensive individual technologies, like the before-mentioned building insulation measures for example.

Conclusions and recommendations

This paper has proposed a series of improvements for the assessment of energy savings potentials and costs for countries interested in using this resource for their energy

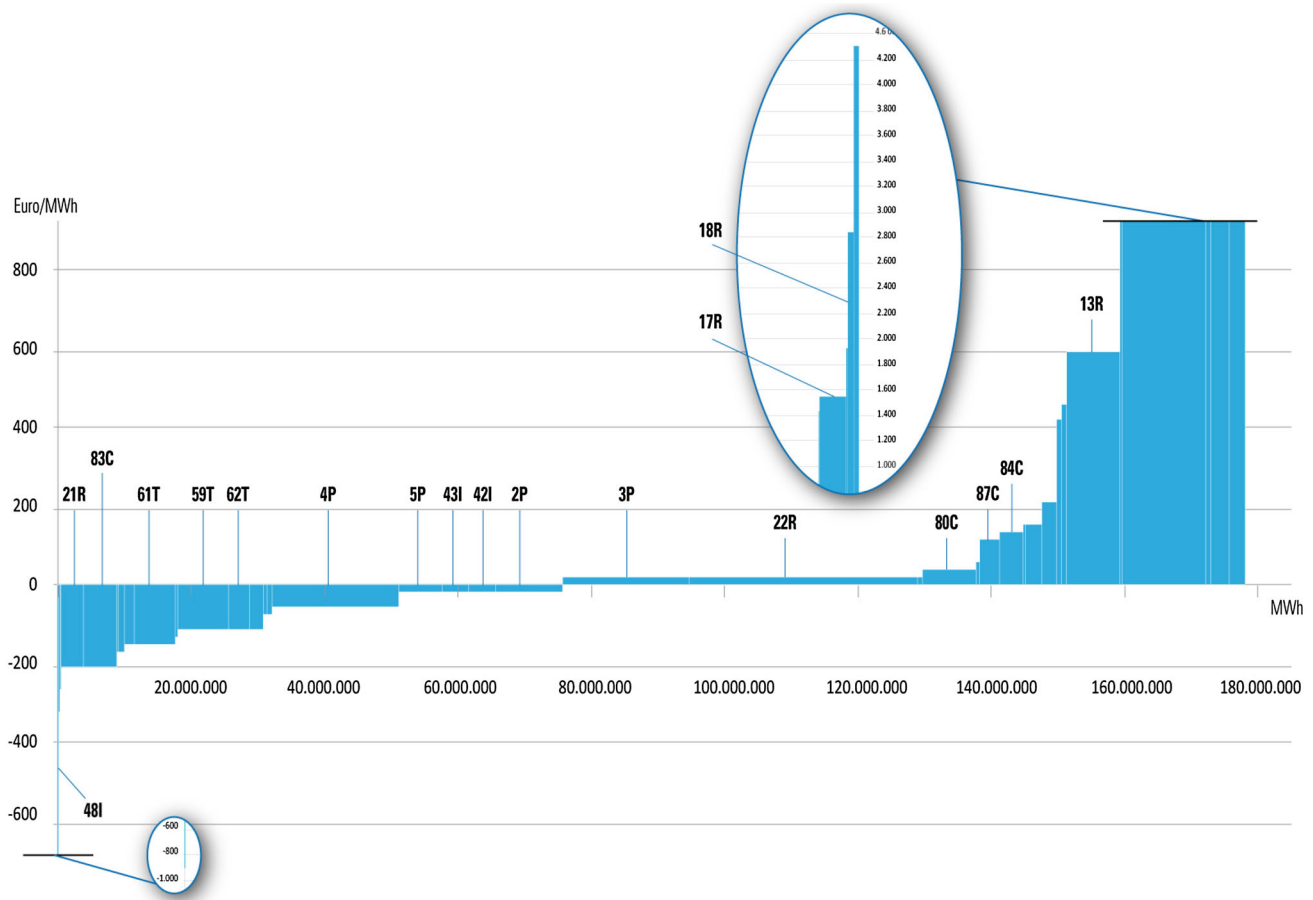


Fig. 6 Energy savings potential for the technological scenario, Spain 2030. Note: Consult the appendix for the identification key of individual measures along the *curve* Source: the authors

transition. As mentioned in the introduction, we believe that energy efficiency should be a priority for countries in the MENA region, in which energy intensities are generally large. We apply our methodology to Spain, a country with many similarities to many countries in the MENA region, both regarding energy mix and structure of energy demand.

Our results show that, for countries in which energy efficiency policies have not been strongly pursued, there is a large energy savings potential, at a very affordable cost for many of the available measures. In fact, the default expected technological progress together with the application of currently existing (and rather standard) policies would be able to produce a significant reduction of energy demand. The study suggests that energy demand in 2030 could stabilize at its 2010 level. This would correspond to a reduction of 26% relative to the situation without the technological changes. Beyond this reduction, the implementation of more aggressive policies or an accelerated evolution of certain technologies could untap even more savings. As shown by the political scenario, promoting the use of the most energy-efficient technologies would yield

reductions of 19% over the expected 2030 scenario. The study does not, however, include the effects of changes in behavior. Hence, new awareness policies or price signals (for example through taxes) might produce even larger energy savings.

The results are also remarkable regarding the overall costs of energy efficiency measures. Even though the interaction or overlap of different technologies has been taken into account, and in spite of very high discount rates for residential consumers, all scenarios show that over 40% of the reduction potential is achievable at negative costs. And savings over 60% would be achievable at prices below 50 €/MWh (note that 50 €/MWh is below the fuel price considered for basically all fuels in 2030). The comparison of results from different scenarios also highlights the crucial importance of energy prices: a reduction in natural gas prices, as assumed in the technological scenario, results in considerably higher costs of energy saving measures. This is because the energy savings translate into lower economic savings for investors. Therefore, it is particularly important to ensure that energy prices include all costs, to provide the right signals regarding energy savings.

Another important conclusion is that a large reduction potential originates from the application of current policies. It is therefore crucial to ensure that these policies are implemented correctly and completely. As a matter of fact, the policies foreseen for Spain include the support of the cheapest and most efficient technologies such as the substitution of old water boilers in buildings or reduction measures in transport.

Regarding the most attractive sectors and measures we must distinguish between the baseline scenario and the more ambitious scenarios. For the baseline scenario it would be crucial to ensure the implementation of renewable electricity technologies, the reduction of energy consumption in vehicles (through hybrids and also through efficiency gains for all remaining fuel cars), the modal change from road to rail, and efficiency gains in climatization of buildings (efficient heaters and heat pumps). For the political scenario, given that the potential for modernization of heating technologies is already partially depleted, the most attractive energy saving measures are wind energy, vehicle improvements, or a modal switch towards rail for freight transport. The technological scenario, on the other hand, points towards the technologies with the largest potential for technological progress: efficient lighting, and hybrid or electric cars. In this case it would be paramount to ensure that the technological progress actually materializes and that the costs fall (this might require additional efforts in R&D).

It is interesting to note that, for all scenarios, building insulation measures are not attractive, in spite of their relatively large reduction potential. The high cost per unit of reduction increases further if the overlap with other technologies is considered (substitution of old heating systems by more efficient ones, for example). This effect is magnified under the private perspective reported in this article.

In any case, we observe large reduction potentials that are achievable at low cost. But the task of really tapping these reduction potentials seems complicated. The abundance of technologies with negative costs hints at the existence of several non-economic barriers that impede implementation. These barriers must be tackled by energy policy, and the implementation costs for the consumer should be an important pillar for the design of these energy policies.

Another very interesting conclusion of the study is that not all energy efficiency measures should be treated in the same way. In the following table we differentiate the measures according to their economic cost and to their energy reduction potential, since we believe that this should determine the type of policy that should be used to promote them. We only present the results for the political scenario, as a reference (Table 4).

The measures with very negative costs are those more interesting to promote from the public point of view, since they provide a large savings potential at a negative cost.

However, the fact that the cost is so negative, and that they are typically not adopted, points that it is not the economics what prevents their implementation, but rather the existence of other barriers: hidden costs, transition costs, insufficient awareness, behavioral inertia, principal–agent problems, technological lock-in, non-socialized risk, etc.

Therefore, the policies to support these measures should focus not on improving its profitability (for example through the typical subsidies or fiscal interventions), but instead should aim at the elimination of the implementation barriers. This includes:

- Environmental or energy awareness policies.
- Institutional reforms that align interests and objectives (for example regarding the principal–agent problem).
- Measures that uncover hidden costs.
- Administrative reforms that reduce transaction costs.
- Financial schemes that reduce or socialize risk.
- Investments in infrastructure to prevent technological lock-in.

Concrete examples would be investments in intermodal transport hubs and new infrastructure that allow for a modal change in transport; to facilitate the use of wastes in the cement industry; audits to raise awareness in industry about available saving potentials; awareness programs to substitute inefficient old water boilers and heaters, etc.

At certain occasions, one might consider economic support or price signals, but these should always be designed to eliminate barriers. In some cases subsidies or price signals can rupture inertia or create awareness. But since their effect is usually temporary, these policies should be of limited duration.

Of course, what is always needed is that energy prices account for all costs. We see in this group wind energy, which may be cheaper than other electricity generation alternatives, but only as long as externalities are included in gas prices. If energy prices are kept artificially low with subsidies, there will be energy efficiency measures which will not be competitive any more.

Regarding negative cost, low potential measures, they would require measures similar to those commented above, because again what is needed is to remove non-economic barriers. But in this case, given that potential is low, and that these policies are generally difficult to implement, one might question the need to promote these measures.

The second group of measures and technologies consists of those with low (positive) cost and high potential. For the public administration, it may also be attractive to support these measures. Within this group we encounter two cases: measures like the previous ones that are subject to barriers (in that case the analysis of the previous paragraphs applies here as well); and measures that do not require additional support, because the low costs already make them

Table 4 Classification of measures in terms of cost and potential (Political scenario)

High potential		Low potential	
Very negative cost		Very negative cost	
Power	Wind onshore	Commercial	LED lighting
Transport	Freight transport by train	Transport	Electric vehicle
Transport	Efficient passenger train	Ind. refining	Process improvements
Ind.cement	Improvements in processes and wastes	Residential	Fluorescent lighting
		Residential	LED lighting
		Transport	Plug-in electric vehicle
		Commercial	Climatization management
		Transport	Biodiesel truck
		Transport	Electric bus
		Transport	Hybrid bus
		Residential	Biomass water heater
		Ind. steel	Energy management EAF
		Ind. ammonia	Energy management
		Ind. aluminum	Process improvements
		Commercial	Biomass water heater
		Ind. steel	Energy management BOF
Low cost		Low cost	
Transport	Low-resistance tyres	Residential	Efficient fridges
Power	Solar thermoelectric	Power	Tidal energy
Residential	Solar water heater	High cost	
Power	Solar PV	Residential	Climatization management
Commercial	Wall insulation	Commercial	Solar water heater
Power	Wind offshore	Residential	Geothermal heat pump
Ind. cement	Precalciners	Residential	High efficiency induction kitchen
High cost		Commercial	
Residential	Wall insulation	Commercial	Efficient heat pump
Residential	Advanced heat pump	Commercial	Double glazing
Commercial	Efficient electric appliances	Commercial	Geothermal heat pump
Residential	Double glazing	Residential	Efficient washing machine
		Residential	Efficient dishwasher
		Residential	Efficient oven

attractive and they are not subject to non-economic barriers. In the latter case, no particular policies are required except for those that ensure that the energy prices include all costs (and hence the private return equals the social one).

Low cost, low potential measures require a careful assessment. If their low cost is real (in social terms) and there are no significant barriers for their penetration, they will not need additional policies, and the market will take care of them. If there are barriers, then we should implement policies similar to those mentioned for negative cost measures. But again, efforts should not be large due to their low potential.

Finally, for high cost, high potential measures, there may be different situations. If the public costs are low while the private costs are high, this may indicate a

concrete problem of environmental or energy externalities, or inefficient risk assignment. In that case the appropriate policies would be those that correct for the externalities, typically through price signals.

If the public costs are high as well (this is the case for residential insulation measures, for example), the following aspects should be considered. First, one must determine the amount of acceptable cost of energy savings: energy savings are desirable, but not at all cost. Therefore, it is necessary to evaluate these costs carefully, including all externalities (two particularly relevant examples in the field of energy are climate change and energy security). It is also recommended to reconsider the construction timelines of infrastructure and the technological lock-in. This is highlighted by Vogt and Hallegatte [24].

Secondly, supporting technological progress can be an attractive option since this makes energy saving measures cheaper; the technological scenario of our analysis illustrates this. In fact, R&D efforts should concentrate on those measures with high reduction potential but high costs, the goal being the reduction of the implementation costs.

And finally, we recommend assessing the ripple effects of these actions outside of the energy sector. A good example is the energy retrofitting of buildings, which is one of the least attractive measures in economic terms. However, this measure has large implications for economic activity, and it provides stimulus in key sectors such as the construction industry. The renovation of cities and neighborhoods is another positive consequence from a social point of view. Consequently, it can be worthwhile to support these measures, in spite of their poor individual pay-off in energy terms.

We have not said anything about high cost, low potential measures: there should not be pursued due to their very low social and private returns.

To conclude, we would like to highlight again that the results of investigations like the one presented in this article depend heavily on the assumptions regarding costs or potential penetration of measures. These parameters are subject to significant uncertainties, and results could change significantly. Sensitivity and robustness analysis are required before actually implementing any strategy in this regard. Another important issue which is not addressed in the paper is the timing of the implementation of the measures proposed. When a target needs to be met, the time needed to deploy a certain measures should also be considered as an additional criterion for decision-making, not only costs and potential.

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Appendix

Energy saving measures–identification key

Code	Sector	Description
1 P	Power	High efficiency gas combined cycle
2 P	Power	Solar PV
3 P	Power	Solar thermoelectric
4 P	Power	Onshore wind
5 P	Power	Offshore wind
6 P	Power	Hydro

Code	Sector	Description
7 P	Power	Tidal energy
8 R	Residential	Biomass boiler
9 R	Residential	Micro-cogeneration
10 R	Residential	District heating
11 R	Residential	Condensating gas boiler
12 R	Residential	Heat pump
13 R	Residential	Advanced heat pump
14 R	Residential	Geothermal heat pump
15 R	Residential	Low-temperature gas boiler
16 R	Residential	Advanced cooling
17 R	Residential	Home insulation
18 R	Residential	Double glazing
19 R	Residential	Thermostats
20 R	Residential	Fluorescent lighting
21 R	Residential	LED lighting
22 R	Residential	Solar water heater
23 R	Residential	Condensating water heater
24 R	Residential	Biomass water heater
25 R	Residential	Efficient fridge
26 R	Residential	Efficient oven
27 R	Residential	Efficient washing machine
28 R	Residential	Efficient dishwasher
29 R	Residential	High efficiency cooking stove
30 I	Industry-ammonia	Hydrogen recovery
31 I	Industry-ammonia	Low-pressure synthesis
32 I	Industry-ammonia	Energy management
33 I	Industry-bricks	Gas recovery–tunnel
34 I	Industry-bricks	Oven insulation–tunnel
35 I	Industry-bricks	Improvements in flow and pressure–tunnel
36 I	Industry-bricks	Upgrade from Hoffman to improved tunnel
37 I	Industry-bricks	Continuous drying–Hoffman
38 I	Industry-cement	Precalcinators
39 I	Industry-cement	Grid cooling
40 I	Industry-cement	Automatization and process control
41 I	Industry-cement	Preventive maintenance
42 I	Industry-cement	Precalculator-wastes
43 I	Industry-cement	Automatization and process control–wastes
44 I	Industry-aluminum	Process improvement
45 I	Industry-petrochemical	Process improvement
46 I	Industry-steel	Energy management–EAF
47 I	Industry-steel	Near net shape strip EAF
48 I	Industry-steel	Energy management BOF
49 I	Industry-steel	Near net shape strip BOF
50 I	Industry-steel	Gas recovery-BOF
51 I	Industry-steel	Upgrade from BOF to EAF
52 I	Industry-oil refining	Process and energy management improvement

Code	Sector	Description
53 I	Industry-ceramic tiles	Oven insulation
54 I	Industry-ceramic tiles	Airflow improvement
55 I	Industry-ceramic tiles	Pre-heating with gas recovery
56 I	Industry-ceramic tiles	Heat recovery
57 I	Industry-ceramic tiles	Change from tunnel to rolling oven
58 T	Transport	Efficient diesel car
59 T	Transport	Electric car
60 T	Transport	Efficient gasoline car
61 T	Transport	Hybrid car
62 T	Transport	Plug-in hybrid car
63 T	Transport	Euro V diesel truck
64 T	Transport	Biodiesel truck
65 T	Transport	Euro V bus
66 T	Transport	Electric bus
67 T	Transport	Hybrid bus
68 T	Transport	Efficient train
69 T	Transport	Rail freight
70 T	Transport	Low-resistance tyres
71 C	Services	Geothermal heat pump
72 C	Services	Biomass boiler
73 C	Services	Micro-cogeneration
74 C	Services	District heating
75 C	Services	Condensating gas boiler
76 C	Services	Heat pump
77 C	Services	Advanced heat pump
78 C	Services	Low-temperature gas boiler
79 C	Services	Advanced cooling
80 C	Services	Building insulation
81 C	Services	Double glazing
82 C	Services	Fluorescent lighting
83 C	Services	LED lighting
84 C	Services	Solar water heater
85 C	Services	Condensating water heater
86 C	Services	Biomass water heater
87 C	Services	Efficient appliances

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