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Evaluating Energy Efficiency Policies with Energy-Economy Models

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Abstract

The growing complexities of energy systems, environmental problems and technology markets are driving and testing most energy-economy models to their limits. To further advance bottom-up models from a multidisciplinary energy efficiency policy evaluation perspective, we review and critically analyse bottom-up energy-economy models and corresponding evaluation studies on energy efficiency policies to induce technological change. We use the household sector as a case study. Our analysis focuses on decision frameworks for technology choice, type of evaluation being carried out, treatment of market and behavioural failures, evaluated policy instruments, and key determinants used to mimic policy instruments. Although the review confirms criticism related to energy-economy models (e.g. unrealistic representation of decision-making by consumers when choosing technologies), they provide valuable guidance for policy evaluation related to energy efficiency. Different areas to further advance models remain open, particularly related to modelling issues, techno-economic and environmental aspects, behavioural determinants, and policy considerations.

1. Introduction

The increased awareness of energy security, continuous escalation of energy prices and growing concerns of global climate change are all contributing to the re-assessment and importance of increased energy efficiency and conservation. Large cost-effective potentials have been estimated (e.g. 25-35 per cent in industrialised countries and above 40 per cent in developing nations) (1). However a number of market and behavioural failures (e.g. environmental externalities of energy production and consumption not reflected in energy prices, asymmetric information, liquidity constraints, bounded rationality of consumers) have traditionally prevented efficiency improvements. Thus, ever-increasing attention has been given to public policy in providing more aggressive and effective instruments to reduce these failures and thus energy demand sustainably. Within this context, the use of bottom-up energy-economy models for evaluating ex-ante energy efficiency policy has gained widespread recognition for supporting energy efficiency policy-making (2, 3).[1] Ex-ante energy efficiency policy evaluation is commonly, though not exclusively, concerned with the simulation and modelling of the impacts of different policy instruments and resulting technological change. However, the growing complexities of energy systems, environmental problems and technology markets are driving and testing most conventional energy-economy modelling tools to their limits.

Bottom-up energy-economy models are of prime importance to support the most suitable design of policies by assessing whether they are capable of achieving the impacts that would justify their implementation. These models are disaggregated models of the energy–economy system that entail a meticulous characterisation of present and emerging energy technologies and can simulate in detail alternative technology futures. They are often driven by exogenously defined macroeconomic and demographic scenarios. Whereas bottom-up energy modelling tools do have advantages, the literature also emphasises disadvantages (4-6). On the one hand, bottom-up models are helpful in exemplifying potential impacts for alternative technology futures and energy demand in detail. They determine emission reduction costs by measuring financial costs and emissions of numerous technologies using a social discount rate (7). These models provide useful policy insights in aspects such as competition of end-use energy efficiency techno-economic potentials; fuel substitution rates and related environmental emissions, among others (4, 8). On the other hand, several studies have elaborated on the shortcomings of conventional bottom-up energy models (9-12). Driven by economic and engineering principles, conventional bottom-up modelling tools often use a traditional „unbounded rational" approach to represent investment decisions and technology choice by the end-user; overlooking critical market imperfections. Bottom-up models assume that market agents have clear preferences and all the necessary information to make their decisions. Besides criticism addressing homogeneity of consumers/firms and their preferences, it is argued that bottom-up models underestimate the intricacy of feedback and learning processes related to the adoption of efficient technologies. In recent years, there has been a growing concern among policy makers and analysts regarding the representation of end users" preferences and realistic policy issues in bottom-up energy models (11, 13, 14).

Against this background, there is very limited detailed literature on the development and use of bottom-up energy models and corresponding assessments addressing technological change driven

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[1] Note that the terms energy models and energy modelling tools are used interchangeably in this document.

by energy efficiency policy, in particular for the buildings sector (15). It is estimated that the building sector (i.e. household and commercial) is responsible for at least 40 per cent of energy use in most countries (16), and offers the largest economic potential for the mitigation of greenhouse gases (GHG) globally (2). As a whole, this sector is estimated to be responsible for one-third of all energy-related CO_2 emissions and two-thirds of halocarbon emissions (15). Despite the growing significance of the building sector in terms of energy and climate change policy, one can discern a lack of literature describing development and applications of the modelling of energy efficiency policies.

To further advance the appropriateness of models from a multidisciplinary energy efficiency policy evaluation perspective, we review and analyse numerous energy-economy models and corresponding modelling evaluation studies, taking energy efficiency policies to induce technological change as the main focus. Using the residential sector as a case study, the research presented in this paper is separated into four parts: (i) review of bottom-up methodologies and corresponding energy-economy models; (ii) comparison between technology choice determinants presented in the literature and those used in the reviewed modelling methodologies; and (iii) the analysis of modelling studies that focus on *ex-ante* energy efficiency policy evaluation. Based on the review, (iv) several research areas to further advance models are identified and discussed. The study covers the most widely used models around the globe to model energy use in the household sector.

2. Reviewed modelling methodologies and tools

The survey presented in this section identifies and describes the various methodological approaches used in bottom-up energy-economy models. Four methodological categories of bottom-up energy-economy models are identified: (i) simulation, (ii) optimisation, (iii) accounting and (iv) hybrid models (5, 14, 17). While not comprehensive, the reviewed models attempt to provide a representative sample of these various methodological categories. See Table 1.

Simulation models provide a descriptive quantitative illustration of energy production and consumption based on exogenously determined scenarios. The methodological approach represents observed and expected microeconomic decision-making behaviour that is not related to an optimal or rational pattern. These models try to replicate end-user behaviour for technology choice considering different drivers (e.g. energy security). Thus, and despite that economic data can be of high significance, drivers are often linked to other aspects of energy systems (e.g. CO_2 constraints). Under this taxonomy we found, for instance, the following models: CIMS; Residential End-Use Energy Planning System (REEPS); and the National Energy Modelling System - Residential Sector Demand Module (NEMS-RSDM).

Optimisation models are prescriptive by definition. They attempt to find least-cost solutions of technology choices for energy systems based on various policy and market constraints. Based on the rational model of consumer behaviour, the allocation of energy supplies to energy demands is based on minimum life cycle technology costs at given discount rates and determined by an optimisation approach (linear programming). Constraints can be related, for example, to atmospheric emissions, fuel supply, technological development and capacity utilisation. Under this taxonomy we found, for instance, the following models: Market Allocation (MARKAL) model generator; PRIMES Energy System Model; and the Model of Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE).

Accounting models aim to primarily manage data and results. These models can be prescriptive or descriptive. Whereas the former can look at the impacts coming solely from the adoption of high-efficient technologies, the latter would approximate the portfolio of technologies resulting from one or various policy instruments. Instead of addressing the behaviour of market agents and resulting technological change, accounting models require modellers to determine and introduce technology choice exogenously. Under this taxonomy we found the following models: Long-Range Energy Alternatives Planning (LEAP); National Impact Analysis (NIA); Bottom-Up Energy Analysis System (BUENAS); Model for Analysis of Energy Demand (MAED); Mesures d"Utilisation Rationnelle de l"Energie (MURE); and the Policy Analysis Modelling System (PAMS).

Hybrid models basically merge different methodological components from the above-mentioned types of models. In addition, some hybrid models are also integrated with top-down or general equilibrium models. That is, there is no need for an exogenously determined macro-economic scenario (employment, income effects, economic growth rate, competitiveness, etc.) but endogenous relationships between the economy and energy system take place instead. Some of the reviewed models fall into this taxonomy. For instance, NEMS combines optimisation, simulation (for each demand sector) and accounting components that provide a general equilibrium system. Likewise, LEAP, PAMS and BUENAS combine elements of simulation and accounting models. In the case of LEAP, the model operates at two levels: (i) built-in basic accounting relationships, such as energy demand and supply, atmospheric emissions, electricity transmission and capacity expansion and costing; and (ii) additional features that modellers can add, such as market penetration of technologies as a function of prices, income level and policy instruments (18). Models such CIMS, MARKAL, MESSAGE, NEMS and PRIMES can also be coupled with general equilibrium models. For instance in MESSAGE, price-driven energy demands are calculated with MESSAGE-MACRO, which is a macroeconomic top-down module that gives hybrid equilibrium features to the modelling tool. Energy demands are endogenously determined by MESSAGE-MACRO in a way consistent with the forecasted GDP and energy prices (19); similar to MARKAL-MACRO (20).

Table 1 also summarises the main structure or components of modelling tools; determinants of energy demand; and coverage of energy services in the household sector. The review shows that despite the variety of methodologies and models reviewed, the growth of the household stock is often used as a key and common driver for determining energy (service) demands. Technology representation is mostly explicit and technologically-rich across all the reviewed models, i.e. they all describe the actual characteristics of numerous household technologies in detail. This is a critical requisite for simulating energy efficiency policy instruments that aim to induce ample technological change. In turn, and regardless the methodological approach, the explicit and rich technological component allows covering a wide range of energy services (e.g. very comprehensive in NEMS and MARKAL). All the reviewed models originate from the OECD region and more than 60 per cent of the identified applications focus mostly on developed countries (as shown in Table 3). To some extent, this finding correlates with the claims about the need for more policy evaluation efforts to assist energy efficiency policy and other GHG mitigation options for the building sector in developing countries (15).

3. Decision frameworks for household efficient-technology choice

This section attempts to reveal the gap between decision frameworks and determinants for technology choice used in different modelling methodologies and the ones used by householders in reality.

3.1. Key technology choice determinants in reviewed modelling methodologies

Within simulation models, decision frameworks for technology choice vary in complexity and incorporate a wide variety of aspects. A complex decision framework is found in REEPS. Here, four decision models forecast decisions made by households: (i) ownership; (ii) efficiency-choice; (iii) usage; and (iv) equipment size. The „ownership decision model" is a discrete choice model. Each generic technology is characterised by utility functions based on exogenous variables, household features and technology characteristics. For example, the estimation of ownership for freezers depends on the following variables: average household disposable income; average number of household members (by housing type); share of rural households in the total population (average); and average electricity price. The „efficiency-choice decision model" is a multinomial logit choice model that forecasts the level of efficiency chosen by the end-user for a specific type of technology. This decision model represents the relationship between purchase price and chosen efficiency. The „usage decision model" estimates energy use for each individual technology on an annual basis, i.e. it forecasts the intensity of usage of technologies based, for example, on floor area (by housing type), heat gain multiplier, efficiency of equipment, and average household disposable income. The equipment „size/capacity decision model" is used to forecast the size/capacity of refrigerators and freezers and HVAC systems. The size of refrigerators and freezers is determined by the specific efficiency choice model but usage is constant.

Another complex decision framework is found in NEMS. It is based on a log-linear function that entails the following key determinants: (i) capital costs; (ii) operating and maintenance (O&M) costs; (iii) equipment efficiency and lifetime; (iv) market share of new appliances; (v) efficiency of retiring technology; and (vi) appliance penetration factors. The log-linear function allocates market shares for competing technologies within each end-use service based on the relative weights of capital and operating costs, discounted annually (21). In the model, market shares are calculated for: (i) equipment decisions related to new housing construction; and (ii) replacement decisions. A time dependent function calculates the capital cost of technology in new construction. A critical input for technology choice comes from fuel price projections generated by the NEMS supply module and the specific technology unit energy consumption. If fuel prices increase noticeably and stay high over time, more efficient-technologies are available earlier in the forecasted period than would have been the case otherwise (22). Taking into account logistic shape parameters[2], a time dependent function estimates the retail cost of replacement technology (21).

Within the reviewed simulation models, CIMS provides a technology choice framework that explicitly addresses and introduces empirically estimated household behavioural parameters – an exception in the reviewed models. When new technology stocks are required, the model simulates technology competition in the economy by determining their market share on the basis of discounted life cycle cost (LCC). However, LCC not only consider financial costs (capital and O&M) and societal discount rates, but also intangible costs that reflect revealed and stated consumer and business preferences in relation to specific technologies and time (23). CIMS attempts to realistically capture consumer behaviour at the technology level using other three key determinants: (i) private discount rate, (ii) market heterogeneity, and (iii) intangible cost factor

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[2] Note that the logistic function (S-shape) is commonly used in consumer choice models.

for each technology (e.g. comfort level). A discrete choice model is used to estimate empirically-based behaviourally realistic parameters for household technology choice (23).

When it comes to optimisation models, decision frameworks follow the cost-minimization rule under certain user-defined constraints (e.g. minimum share of renewable energy). Like in MARKAL or MESSAGE, the objective function is to find the combination of fuels and technologies that minimises total energy system costs, while keeping exogenously determined energy service demands satisfied over a given time period. For each time period, the model minimises the sum of all technologies, all pollutants, and all input fuels of the various costs incurred. Technology choice is driven by factors such as energy prices, discount rates, capital and O&M costs; and technological information about the efficiency and emissions of current and future energy-using devices. Optimal solutions are obtained as long as all the end-use demands for energy services; which are exogenously determined, are met during the time horizon analysed. In PRIMES, decisions in the household sector are represented as a budget allocation problem so energy services are further linked to changes in energy prices and household income. The methodology for the demand sectors assumes economic agents optimising an economic objective function, which for the household sector is utility maximisation (24, 25).

Decision frameworks in accounting models are much simpler than the previous approaches. For this case, the modeller explicitly accounts for the outcomes of decisions instead of simulating decisions of householders as such. Decision frameworks usually encompass the following steps: (i) selection of one or more policy measures that induce technological change (e.g. minimum performance standards as in BUENAS); (ii) selection of the efficient technologies being stimulated (like in MURE); (iii) definition of the technical performance of the selected technologies; and (iv) definition of respective market penetration rates. An important aspect is the relationship between policy instruments and technologies. In MURE (26) a policy instrument is an “intervention enacted by the national or local government or energy agency” to improve energy efficiency, and a technology “is the means by which energy savings are actually saved”. A given technology can be implemented as a result of one or more policy instruments. Therefore, the simulation outcomes are related to the technologies which are driven by a given policy measure.

A critical element in accounting models is the internal consistency of the assumptions driving social, economic and technological evolution that frame the development of a given scenario. For instance in MAED or LEAP the model output is simply a „mirror image" of the scenario assumptions. The expected future trends for each determining factor are exogenously introduced by the modeller. Therefore, the consistency of the model outcomes depends heavily on the understanding that the modeller has of the interrelation and dynamics of various determining factors (18, 27). In certain accounting models, like PAMS or NIA, market penetration rates are estimated by a „shipment model", which is often based on accounting principles that forecast the sales of units and market shares based on the range of lifetimes of the equipment. For example, they can account for technology used to replace retired units, technology shipped to new homes, and technology installed due to fuel switching.

3.2. Key technology choice parameters from the reviewed literature

As noted above, common determinants of technology choice in the reviewed energy models are capital and operating costs. However, the literature provides compelling evidence of a broader picture (28). Kempton and Montgomery (29) find that consumers apply heuristic approaches to decide their energy use, in which purchase costs are ascribed a higher priority than operational costs and resulting savings. In addition, consumers often lack knowledge regarding operating costs (and benefits) related to efficiency improvements, which prevents adopters from fully comprehending the importance of this determinant (30). However, the literature shows numerous non-economic determinants affecting technology choice. Many determinants are described in terms of non-energy benefits including, for instance, improved comfort, noise reduction, functionality, performance, quality, reliability, and design (15, 31-35). Studies also show a positive correlation between knowledge on energy efficiency and environmental awareness (36-38). Furthermore, certain studies also identified a correlation between educational level and investments in energy efficiency (39). The literature also shows that investments in low-energy houses and energy-efficient appliances have been supported by owners in terms of perceived status, social recognition and pride (38, 40, 41). Table 2 shows key determinants of technology choice found for building envelope, lighting and consumer appliances.

From the literature we conclude that decisions practiced for the adoption of household efficient technologies are complex and cannot be captured only by using techno-economic parameters and decision rules associated with capital and operating costs. The literature shows that whereas capital and operating costs are relevant for efficient technologies, they represent only a part of a great variety of determinants that drive consumer's energy-related decisions regarding technology choices (32, 42). Furthermore, even in the presence of perfect information, a larger set of determinants can still lead to irrational utility-maximisation decisions (43).

4. Ex-ante energy efficiency policy studies for the household sector

This section focuses on the analysis of modelling approaches used to evaluate energy efficiency policy in the reviewed energy-economy models. A number of case studies were selected to illustrate how the reviewed models have been used to evaluate policy instruments for energy efficiency in the household sector. In total, more than 20 case studies were analysed (see Table 3). The cases were randomly chosen based on a literature review which entailed the following selection criteria: (i) availability and accessibility of data/information; (ii) applicability to the household sector; (iii) recent or updated information; (iv) material that has undergone some kind of peer review process.

4.1. Main research evaluation goals

Basically all the reviewed cases have their own specific research goals and no generalisations can be made. On the whole though, three main categories of research goals were identified: (i) to demonstrate use of a given energy modelling tool to simulate or forecast technological change; (ii) to focus on impact policy evaluation; and (iii) to explicitly evaluate one or more energy efficiency policy instruments.

First, a number of studies demonstrate the use of a given modelling tool to simulate induced technological change, such as MURE and PAMS. This particular research goal implies the early development stage of models and thus the need to test and validate them at the time of carrying out those modelling exercises. The study done by Cowing and McFadden (44) focused on a detailed comparative evaluation between the REEPS model and the Oak Ridge National Laboratory (ORNL) model. A more comprehensive research goal is found for the CIMS model.

In an explicit effort to address key flaws found in bottom-up models, such as lack of behavioural realism and homogeneity, Jaccard and Dennis (23) apply discrete choice modelling for the empirical estimation of behavioural technology choice parameters.

Secondly, most of the reviewed case studies have policy impact evaluation as their research goal, e.g. (45-49). Note that „policy impact evaluation" is different from „policy outcome evaluation" (50-52). Whereas an outcome is understood as the response to the policy instrument by subject participants (e.g. adoption or learning processes related to new technologies), an impact is understood to be the resulting changes generated by outcomes on society and the environment (e.g. emission reductions, energy savings or improved energy consumption patterns).

Thirdly, and to a large extent, the majority of the case studies focus on the assessment of policy instruments and related scenarios. For instance, Jaccard and Dennis (23) analyse with CIMS the impacts of subsidies for home retrofits and high efficiency heating systems on GHG emission reductions in Canada. Yanbing and Qingpeng (53) with LEAP focus on the impacts related to the implementation of different policy instruments targeting the Chinese building sector. Using MARKAL, the research goal of Božić (54) is to evaluate the impacts of DSM measures and labelling programmes (among others energy policy instruments) for a group of islands in Croatia. Based on different evaluation criteria, Mundaca (55) analyses the implications of implementing a tradable certificate scheme for energy efficiency improvements at the EU level. All the reviewed cases carried out with NEMS-RSDM also entail the explicit research goal to analyse a variety of policy instruments in the building sector, such as taxes, performance standards and building codes. Using PAMS, van Burskirk et al. (56) focus also on standards and Iyer (57) on labelling endorsement programmes.

When analysing the research goals of the case studies, we find that policy evaluation and impact evaluation go hand in hand in the reviewed cases. Our review is consistent with the fact that the limited number of energy efficiency policy evaluation studies has traditionally targeted the narrow, albeit challenging area of impact evaluation, in terms of energy savings, emission reductions and energy savings costs (58-61).

4.2. Modelling approaches to address market barriers and market and behavioural failures

At the risk of stating the obvious these days, energy efficiency improvements are constrained by a number of market barriers and market and behavioural failures. They include information asymmetries, the „principal-agent" problem, lack of incentives for careful maintenance, external costs of energy production/consumption not included in energy prices, bounded rationality of energy users, lack of adequate capital, transaction costs, etc. See for instance (30, 43, 62-64). The question is how and to what extent these barriers and failures are captured in the reviewed modelling exercises.

The analysis shows that market and behavioural failures are often not explicitly captured. We find that, to some extent, they are incorporated through high discount rates (see more below). One can assume that market imperfections are at least partly taken into account in the historical data used for setting the baseline scenario for analysis. For instance, the work done with the NEMS

(65) model considers that “the reference case projections are business-as-usual trend forecasts, given known technology, technological and demographic trends, and current laws and regulations”. Similarly, the work done with the NIA modelling tool uses a „shipment model" that forecast shipments of efficient technologies based partly on „historical trends" to set the baseline case. The work done by Kadian et al. (47) assumes in the business-as-usual scenario that “historical trends will continue”. In other words, one can infer that existing failures remain in place under business-as-usual or baseline scenarios. However, no details are given regarding those specific and existing failures or how they have been already reduced or overcome due to the existing portfolio of policy instruments. An attempt is made by Morales and Sauer (46), in which several market barriers are mentioned (e.g. lack of information, high capital costs). Although there is an implicit understanding that these barriers are incorporated in the baseline scenario, no details are given about how they were introduced or handled.

The review shows that high (implicit) discount rates are sometimes used to approach or mimic market and behavioural failures (54, 55). Extensive literature shows that households use high implicit discount rates (50 or 200 per cent) leading to low/slow adoption of (high-first cost) energy-efficient technologies. See for instance (63, 64, 66-70).[3] Specific causes of high implicit discount rates include a lack of information about cost and benefits of efficiency improvements, a lack of knowledge on how to use available information, uncertainties about the technical performance of investments, a lack of sufficient capital to purchase efficient products, high transaction costs for obtaining reliable information, risks associated with investments (69-71).

Once policy instruments are modelled, high discount rates are then lowered to reflect „real" or „social" rates to mimic household preferences for efficient technologies in positive response to policy instruments, such as information campaigns and labelling programmes. However, this modelling approach has been criticised. The literature points out numerous limitations to infer inefficient market behaviour from such high implicit discount rates. These include omitted transaction costs that householders are likely to bear; miscalculation in equipment costs and/or energy savings; and need for compensation for risk (63, 72, 73). Furthermore, it is argued that household investments in energy efficiency (e.g. retrofits) might correctly use high discount rates because investments are illiquid, risky and, for example in the case of home insulation, have long payback periods (72, 74).

On the other hand, the use of high implicit discount rates to represent market imperfections should be compared to the modelling approach of using „real" or „private" discount rates – as also used in some cases. The reviewed models indicate that the real or private discount rates applied are in the range of 3-20 per cent. For instance, the PRIMES model uses a discount rate of 17.5 per cent for the household sector and the NIA tool uses discount rates of 3 and 7 per cent to assess minimum energy efficiency performance standards. These discount rates are often applied under the assumptions of „well-defined consumer preferences" and „unbounded rationality". Consequently, their use generates optimistic penetration rates for efficient technologies. Once the future costs of capital, operation and maintenance, fuel consumption, abatement control equipment, etc. are calculated and translated into present values, many energy-efficient technologies emerge as profitable under different policy scenarios. However, this modelling

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[3] Implicit discount rates are often estimated by comparing future savings in operating costs with initial capital or purchase costs.

approach has also been criticised because of the critical assumptions mentioned above and also because a single ex-ante financial estimate of lifecycle costs embodies the full ex-post social costs (i.e. externalities) of technology choice (75).

4.3. Policy instruments and corresponding modelling approaches

Policy instruments are the key means or operational forms by which governments attempt to reduce or eliminate barriers that hinder increased energy efficiency, modify the behaviour of subject groups and thus attain policy objectives. Using the „resource approach" (76, 77) as a departure point to classify policy instruments, we identify a variety of instruments targeting the household sector in practice. Based on Levine et al. (15) and Vedung (77) we classify energy efficiency policy instruments into three main categories (i) economic, financial and market-based instruments, (ii) regulatory approaches and (iii) informative and voluntary schemes.[4] See Table 4.

Note that the categories depicted in Table 4 attempt to frame certain conceptual considerations when addressing modelled energy efficiency policy instruments. We do acknowledge that it is difficult to draw a clear line between policy instruments as they often share common (e.g. legal) ground (78). Table 4 shows that there is a great variety of policy instruments implemented. The question is now which policy instruments are usually addressed in modelling studies and how.

The majority of the cases focus, either implicitly or explicitly, on minimum performance standards and building codes. One explanation for this lies in the fact that some of the selected models were specifically developed for such purpose (e.g. PAMS, NIA, BUENAS). Another possible explanation is the relatively simple modelling approach needed to do so. The way the modellers represent or mimic performance standards is mainly through modification of efficiency rates, technology market availability and penetration rates.

Next to performance standards and building codes, the majority of the policy instruments being modelled are economically-driven in nature. Taxes and subsidies dominate the area of economic policy instruments being modelled. Modelling approaches for these economic instruments involve the effects on capital and/or operating costs and the resulting adoption rates. For instance in the NEMS-RSDM and MARKAL models, rebates used in demand-side management programmes can be modified by the user directly at the equipment level. This seems to be the dominant modelling approach, as economic criteria are used as the major driver for technology choice.

Informative policy instruments were identified as being much less modelled compared to economic ones. These types of instruments, including communication campaigns and labelling of equipment, work through the provision of information of knowledge to accomplish or preventing social change. In some cases, awareness raising campaigns and labelling endorsement

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[4] Note that another resource-approach taxonomy of policy instruments comes from the environmental economics literature, in which the common typology of policy instruments differentiates between two types: (i) command-and-control and (ii) market-based instruments.

programmes are addressed (47, 53, 79). However, a lack of explicit modelling methodological details prevents any analysis in this regard. In other cases, the modelling approach is simplified to the extent that technology adoption targets driven by these policy instruments are based on expert knowledge, e.g. (45). Alternatively, higher market shares for qualifying technologies in comparison with standards technologies are set under modelling exercises addressing labelling programmes – see (57). From our review, one can safely say that the modelling and evaluation of policy instruments addressing consumer behaviour through informative policy instruments remains a challenge for the modelling community.

When it comes to the determinants used to model the identified policy instruments, the majority of the reviewed case studies have addressed policy instruments through technical factors and costs of measures for efficiency improvements. In turn, this gives little room for the representation of informative policy instruments. Again, this approach departs from the critical assumption that we can mimic policy instruments using economic and engineering criteria as the primary driver for decision making and corresponding technology choice. Some aspects deserve our attention:

- Most of the reviewed models offer various economic and engineering „policy handles" that allow the modelling of policy instruments: For all the reviewed cases, technologically-driven policy advancement in equipment design and efficiency are modified at the equipment level. For example, the „policy handles" in REEPS include a variety of economic and engineering factors, among them, capital and O&M costs; functional forms and coefficients for choice equations; pre-failure replacement/conversion decision algorithms; restrictions on legal or market availability of specific technologies; and modification of efficiencies of specific technologies. Another example can be taken from NEMS-RSDM: building shell features can be adjusted in the model to represent building codes or the impact of energy-efficient financial incentives.
- There is the common practice of using exogenously determined high market penetration rates, usually based on expert judgement for policy-driven efficient technologies – with the exception of models that entail a „shipment model" to forecast estimates of sales and market share of efficient product in the presence or absence of policy instruments. For instance Kadian et al. (47) and Yanbing and Qingpeng (53) assumed „moderate" to „high" market penetration rates for efficient technologies when modelling labelling and performance standards. The work done by Božić (54) uses high market penetration rates for household technologies when modelling DSM measures. All reviewed cases using MURE (80-82) use different annual penetration rates to model policy-driven technologies (e.g. space heating, hot water). Economic and regulatory policy instruments previously noted can be modelled and reflected qualitatively in MAED. However, the quantification of the driving factors for mimicking policy instruments also needs specific data and expert judgment (A. Hainoum, unpublished information).
- Another common way to model policy-driven efficient technologies is to use efficiency ratios higher than the baseline. The value of efficiency parameters is user-defined and often based on expert knowledge or input provided by equipment manufacturers. Yanbing and Qingpeg (53) used higher efficiency ratios for HVAC systems (relative to the base case scenario) as key modelling parameter. Similarly, all the case studies related to MURE use high efficiency ratios to assert the impact of numerous policy-driven technologies. For instance, for more efficient building envelope the following parameters were modified: (i) average u-value of new buildings; (ii) average u-value of walls; and (iii) average u-value of windows. In other words, the lower the u-values of external building constructions materials/elements, the lower the energy input required for heating purposes. The reviewed work with NIA to analyse minimum performance standards involves high efficiency ratios for technologies relative to

the baseline of the model equipment. On the whole, the use of efficiency ratios or lower energy consumption values helps to by-pass the development of large and specific technological databases.

Despite the fact that economic and engineering aspects are the dominant technology choice determinants in all the reviewed cases, we identify some modelling efforts that attempt to have a more comprehensive approach. Jaccard and Dennis (23) design and apply a discrete choice model to realistically capture and estimate consumer behaviour parameters for technology choice. In addition to capital and O&M costs, the modelling exercises with CIMS use private discount rate, market heterogeneity, and intangible cost factor to determine the market share of efficient technologies. Using the empirically estimated household parameters, the study then simulates policy instruments (e.g. subsidies for home retrofits). Another case is found in Richey (83) and Koomey (84). Both analyse the consumer response to a tax rebate with NEMS. Resulting shipments are divided into two components: (i) the „announcement effect", which represents the consumer response to the tax rebate, independent of the rebate level; and (ii) the „direct price effect", which represents the consumer response to the rebate level as such. In addition to the „announcement" and „direct price" effects, a „learning rate" (or so-called „increased production experience effect") of 20 per cent is used to forecast decreases in future capital costs relative to currently installed costs data due to increased production experience (i.e. a learning rate of 20 per cent illustrates a cost reduction of 20 per cent for each doubling in the number of sold units). The impact of the tax rebate is calculated in terms of the increase in market share due to the rebate and resulting forecasts of high-efficiency technology shipments.

Quantitative targets, in the form of CO_2 or energy saving targets/constraints, are also applied as a key modelling departure point in some cases. Mundaca (55) use energy saving as a key element to model tradable certificates for energy efficiency improvements with MARKAL. The modelling approach sets mandatory energy saving targets as user-defined constraints for quantifying cost-effective energy efficiency potentials under a hypothetical EU-wide scheme. Schulz et al. (48) also analyse primary energy reductions combined with CO_2 emission caps applied to the Swiss MARKAL energy system. As concerns the household sector, the focus is on heating-related technologies. Kannan and Strachan (49) also use an emission cap as a central element in its modelling approach. The study explores technological pathways in the household sector for achieving an economy-wide CO_2 emission reduction target by 2050 of 60 percent in the UK MARKAL energy system.

5. Critical dimensions to further advance modelling of energy efficiency policy

This section seeks to provide a basis for the discussion of the further feasibility and appropriateness of the bottom-up energy-economy models to evaluate energy efficiency policy instruments. In the light of findings, we identify aspects that can further advance energy modelling tools in relation to energy efficiency policy evaluation for the household sector. Note however, that most of the discussed issues can be applicable to other end-use sectors as well.

5.1. The modelling dimension

A transparent modelling effort that provides all the necessary information is critical. During the development of this review, our work was sometimes challenged by limited access to related-model and/or modelling documentation. Technology databases are sometimes kept by research groups who are not willing to share this critical input with the rest of the research community. Undoubtedly, the development of such databases is highly resource-intensive so this practice might be sustained by economic and strategic arguments. However publicly available model documentation, detailed data implementation guide (including data quality and related uncertainty), and explicit model assumptions are central to provide a solid foundation for policy makers and the research community to better evaluate the superiority and significance of the model and modelling results. Advantages and disadvantages of modelling tools should be provided explicitly to better understand and judge whether the model under use has been selected to answer the policy questions. This approach would allow policy makers to have a better idea about the competing modelling methodologies and approaches to energy efficiency policy. The literature emphasises that policy makers sometimes seem to be frustrated because the same modelling tool is used to answer any type of policy questions (4, 6).

Constant model verification and validation is needed. Due to the fact that energy efficiency is a moving policy target, additionality, assumptions and data related to efficient technologies need to be carefully scrutinised and periodically updated. Models and databases need to be constantly validated against the energy system/market from the perspective of the research objectives and policy questions. Whereas selected policy instruments and best available knowledge are incorporated at the time of model"s creation, new data, new policy instruments and new ex-post outcomes are emerging all the time. Thus, these aspects should be analysed and incorporated as much as possible to reflect the dynamics of energy efficiency markets and policies. In turn, this will enhance the credibility of BAU scenario(s) used to make comparisons. On a regular basis, an open peer review process can greatly support model verification and validation, which are essential for model development.

Another aspect relates to an explicit elaboration of the methodology to mimic energy efficiency policy instruments. It is necessary to provide clear information about the methodological details on how a policy instrument is actually represented, i.e. what is the model language (e.g. variables, parameters, assumptions, judgements) being used by the modeller to represent the policy instrument under enquiry? The modelled representation of the instrument needs then to be compared with the most likely form that the same policy instrument is supposed to take in reality and under different policy circumstances (14). For instance, to model a subsidy by simply reducing the capital costs of all efficient technologies one needs to consider that in reality those technologies might be subject to additionality tests before they actually qualify for the scheme (e.g. technologies that are profitable in the short-term do not qualify). Modelling studies should provide this comparative exercise to transparently reveal the gap to better to judge the appropriateness of the modelling approach. Likewise, methodological details are needed concerning how the policy instrument(s) under analysis is supposed to reduce or eliminate market and behavioural failures.

There is a need to enhance the interpretation of modelling outcomes by explicitly linking the advantages and disadvantages of the model and the modelling approach undertaken, with guiding research questions, scenario development, assumptions and input data concerning quality and related uncertainty. Within this context, much more attention should be paid to the sensitivity of the results to the assumptions and parameters used in the modelling exercise. Point estimates are subject to errors but the variance of a parameter determines uncertainty and provides better precision with which the estimate has been produced. Thus, confidence interval estimations should be used more to account for uncertainty levels. The choice of the confidence level (e.g. 95 or 90 per cent depending on the needed accuracy of the forecasted energy savings) could be left to stakeholders if a stakeholder-based modelling exercise is carried out. Estimations of confidence levels should be as essential as errors bars on experimental data.

Complementary research methods are needed to better comprehend the broad effects and attributes of energy efficiency policy instruments. It has been already argued that there is no single best energy-economy model that can answer all policy questions (4, 6). From the methodological point of view, the appropriateness of „triangulation" is confirmed throughout our review (85). That is to say, a variety of methods for analysis are needed to address the empirical and normative understanding of energy efficiency policy instruments applied to the household sector (e.g. surveys, agent-based modelling, cost-benefit analysis, intervention theory, Delphi method, interviews and statistical analysis, top-down models). What is usually needed in policy analysis is a portfolio of methods for data collection and analyses to perform the overall evaluation of (and comparison for alternative) policy instruments. The use of different but appropriate research methods can provide an extensive foundation for more balanced policy discussions and may contribute to improved communication among stakeholders. Policy makers may have stronger grounds on which to justify policies to stakeholders.

5.2. The techno-economic and environmental dimension

The integration of co-benefits should be a central research component for models and modelling studies. Efficiency improvements can reduce atmospheric pollution; lessen negative externalities resulting from energy production; boost industrial competitiveness; generate employment and business opportunities; improve the housing stock and the comfort level of occupants; enhance productivity; increase security of supply; contribute to poverty alleviation, etc. It has been argued that non-energy benefits of efficiency improvements are not usually included in energy efficiency (modelling) evaluation studies, underestimating the economic potential of increased energy efficiency (14, 15, 86). The fourth IPCC assessment explicitly acknowledges the need to integrate co-benefits in GHG mitigation studies for the building sector, and into related policy decision-making processes (15). With the exceptions of Jaccard and Dennis (23), that introduces comfort level in terms of air quality; and Mundaca (55), that accounts for avoided external costs such as morbidity, loss of amenities, and the impacts of global warming, no other explicit attempts were identified to integrate co-benefits. It is however fair to acknowledge that a broad and explicit quantification of co-benefits (including monetary aspects) poses a serious challenge for a thorough modelling evaluation exercise. Therefore, specific methodological aspects need to be developed for integrating workable co-benefits into the modelling tools, as well as providing guidelines on how to address more subtle and product-related co-benefits (e.g. noise reduction and comfort from triple glazing). Ex-post evaluation addressing the order of magnitude of non-energy benefits is a central to support this critical research task.

Another area for further research relates to the analysis and introduction of transaction costs (TCs). TCs for any investment involve expenditure that is not directly involved in the production of goods or services but is essential for realizing the transaction (87). There is extensive literature on the theoretical and empirical aspects of transaction costs and their negative impacts on energy efficiency policy instruments – see e.g. (30, 88-90). However, the reviewed case studies often underestimate this critical issue and a lack of quantitative treatment was discerned. Transaction costs usually arise from due diligence, the search for and assessment of information, negotiation with business partners, acquisition of legal services, measurement and verification of the actual level of improvement, etc. By making new measures seem more expensive than conventional ones, transaction costs can thus favour inefficient or standard household technologies, making potentially profitable investments completely unattractive (30, 90). The inclusion of transaction costs analysis will improve the estimations of household energy efficiency potentials; however, the information gap needs to be covered with more empirical research. Therefore, ex-post policy evaluation on TCs is needed in order to feedback modelling efforts. In turn, an improved modelling tool in this regard will allow better simulating policy instruments attempting to specifically reduce sources of TCs.

There is a need to explore synergies among modelling tools to further improve cost-revenue specifications and the accuracy of aggregated results. With some exceptions (MURE, NIA, PAMS), technology costs per unit of energy savings, and the cost of unit energy are critical aspects for which details were difficult to identify. From the end-user perspective – an important analytical and policy decision-making ingredient – a cost-revenue analysis has to be carried out usually outside the model. Synergies among different modelling tools to further enhance cost-revenue ratios and related results were found only for the case of PRIMES combined with the use of the MURE database. The combined use of accounting models more single-technology-oriented in nature (e.g. MURE, PAMS or RETScreen[5]) with those that are more energy-system-oriented (MARKAL, MESSAGE) should be further pursued. Within this context, a major goal for the energy efficiency modelling community should be the exploitation of the combined capabilities and strengths to advance the understanding of technology markets and policy issues.[6]

The use of experience curves offers a supportive research method to study past cost developments that in turn allows analysis of future cost development. Learning rates are derived based on the results of experience curve analysis. Experience curves and associated learning rates have been already adopted in bottom-up modelling studies; however, attention has focused heavily on energy supply technologies (91, 92). The modelling exercise performed with the NEMS model for tax credits shows that it is possible to apply experience curve analysis for end-use technologies. In addition, PRIMES includes learning-by-doing curves and parameters that can represent perceived technology costs by end-users. It is known that efficient technologies have a marginal market share once they are introduced, but cumulative production can increase rapidly during early stages of commercialisation, bringing with it sizeable opportunities for cost reductions related to increased production. Research by Weiss et al. (93) for end-use technologies can be taken as a departure point.

5.3. The household-behavioural dimension

It has been long argued that bottom-up energy models provide an unrealistic portrait of microeconomic decision-making frameworks for technology choice. The key question is to what extent a better representation of empirically estimated determinants of choice is actually feasible in energy modelling. Which determinants are more workable than others in improving such tools? How can one assess the specific influence of certain parameters on technology choice? With the exception of the work done by Jaccard and Dennis (23) no other reviewed modelling work attempts to answer these types of questions. Nevertheless, one has to acknowledge that even if modellers are sometimes fully aware of the need for a better representation of microeconomic decision-making frameworks, there is still limited empirical work and practical research on how to handle and convert qualitative knowledge about household behaviour into a set of quantitative

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[5] For further information see http://www.retscreen.net/

[6] Similar to the work done under the Energy Modelling Forum. For further information visit http://emf.stanford.edu/

parameters (14). Importantly, the estimation of technology-related market response parameters is usually based on historical data. Thus, this issue is of prime importance when analysing the role of new efficient technologies in relation to household behaviour for which no or very limited data yet exist. Another issue to take into account is that household technology choice is often affected by a number of intermediaries (e.g. project developers, construction companies, equipment dealers) (32, 94). Some studies show that intermediaries" incentives to pursue energy efficiency are few, while their disincentives are many (95-97).

To support the development of comprehensive microeconomic decision-making frameworks, outcomes from social marketing research and social psychology need more attention (14, 98-100). Whereas the latter discipline focuses largely on aspects related to individual/group behaviour and critical factors behind it, the former discipline aims for the systematic application of marketing strategies to influence those factors and attain specific behavioural goals. These social disciplines can provide important insights into household preferences for efficient technologies; broadening the economic-engineering approach that dominates energy-economy models. By drawing on research outcomes from these disciplines, a better understanding of influence processes can be achieved. This can help identifying and improving mechanisms to effectively target the household sector through better designed, modelled and analysed policy instruments.

Household behaviour in relation to efficient technology choice and market failures is likely to change over time. It is argued that historical data are inadequate to assess different technology futures in relation to market failures and under evolving policy conditions (84) . Furthermore, it is very likely that decision-making frameworks of future generations that are affected by market failures will be different or more complex than the ones we are at least partly aware of today. The statistically-derived relationships embedded in historical data used by modelling studies are precisely the ones that modelled policy instruments aim to change (84). Thus, the explicit or implicit assumption that market and behavioural failures are considered in historical data, or in an implicit discount rate, seems to be part of the policy evaluation challenge itself (14). This aspect is often overlooked but applies when analysing the role of new household technologies for which no or very limited past data yet exist, such as micro wind-energy turbines.

More research is needed on the use of discount rates to mimic market and behavioural failures. Our analysis suggests that even if purely economic parameters are examined – such as discount rates – there is still a gap between the revelations of ex-post analyses and values used in ex-ante modelling exercises. Although high implicit discount rates and related causes have been the most common and frequently mentioned evidence for the low/slow adoption of energy-efficient technologies by consumers (101), the debate regarding the use of appropriate discount rates in modelling exercises continues (74, 75). Whereas the importance of (implicit) discount rates in the context of the „energy efficiency gap" has been long debated – see e.g. (6, 63, 68) – the reviewed cases ignore the possible scale of the effects of discount rate uncertainty. At the risk of oversimplifying, the literature shows that the debate in the mid-1990s on consumer discount rates and energy efficiency technology choice is still present. Therefore, discount rates in the context of efficient technology choice need to be better understood otherwise their usefulness will continue being questioned. This evaluation challenge tells us that more research is needed in order to better understand how current energy efficiency policy instruments actually reduce or overcome the market and behavioural failures that drive the use of high implicit discount rates. Together with social marketing research and social psychology, behavioural economics also has a role to play.

Another lesson arising from our study involves the need for a greater focus on policy outcome evaluation to improve diffusion processes that can complement impact policy evaluation. Research has already indicated different modalities deployed by households for adopting efficient technologies. For example the decision might not be about whether to adopt an efficient technology but rather which version of the technology should be chosen and which determinants influence that decision (102-104). Although technical change is often limited to the dissemination of mature efficient technologies, the involvement of multiple market agents seems to be critical in encouraging households to take a front-line position on energy efficiency (94). A better understanding of technology diffusion patterns and processes should effectively provide dynamic feedback to modelling studies – cf. (105). Research on energy efficiency policy addressing outcome evaluation has been made (52) and should be further developed and integrated in modelling studies.

5.4. The policy dimension

Even if we attempt to predict the impacts of energy efficiency policy instruments with very complex modelling tools, such as NEMS or REEPs, inherent limitations and uncertainties remain. According to Lindgren and Bandhold (106) scenario development is an effective way of reducing an enormous amount of information into a controllable format without over-simplification. Ringland (107) argues that the purpose of scenario development is to manage uncertainties and risk. The literature suggests that a more methodical examination of the impact of uncertainties on scenario results are needed (L. Schrattenholzer, unpublished information). In addition, not only a set of scenarios has to be used but also explicit assumptions about the effectiveness and efficiency of the existing and future portfolio of policy instruments have to be made (108). Modelling studies can provide consistency and add credibility to scenario development exercises by clearly elaborating on the outcomes of future events; nonetheless, energy-economy models should not steer but support that research and learning process (84). In addition, complex and rich modelling results can be of limited value if no guidance is given to policy makers regarding the interpretation and implications of the obtained results. Therefore, modelling results may be better translated into a set of concrete and robust recommendations.

Intervention theory could be tested as a way to support a better representation of policy instruments in modelling studies. This approach can be understood as all the empirical and normative beliefs underpinning public policy interventions and it aims to describe how a policy instrument is likely to work in reality (109). From a systemic standpoint, intervention theory can be used to develop a conceptual model addressing how a given policy instrument is likely to be implemented and how it could or should affect technology choice; including decision-frameworks used by agents or intermediaries. This „implementation framework" could then be used to asses whether decision-frameworks and key determinants embedded in models are capable of better representing energy efficiency policy instruments. A key challenge in this regard may be represented by informative policy instruments and the identification of targeted cognitive processes for inducing technological change.

Policy instruments do not function in isolation. Even though a number of policy instruments were modelled in the reviewed cases, synergies and overlaps among them were often omitted. Our review suggest that the modelling address, to some extent (possibly a large extent), the combined effects of the portfolio of policy instruments. However, the effects (i.e. impacts and outcomes) of a single policy instrument cannot be added with other instruments in an ideal form in modelling studies (14). This emphasises the need to de-link the effects from various energy efficiency policy instruments – the so-called „impact problem" (85).Within this context, it is also relevant to consider the issue of additionality. This is because in principle, any energy efficiency policy instrument encourages energy savings that would not have otherwise occurred under a business-as-usual (BAU) scenario (i.e. as depicted by the baseline or counterfactual situation). However, how the additional component of efficient technologies can be ensured, or dynamically adjusted, if a variety of policy instruments is constantly implemented in the short and long run? It is critical that the current portfolio of policy instruments is taken into account when developing the BAU scenario.

Uncertainties about future policy developments strongly suggest the development of alternative and credible counterfactuals or baseline scenarios in modelling studies. One has to note that most of the reviewed modelling tools and corresponding databases represent historical know-how through relationships that are obtained usually from statistical analysis. Thus, those statistical relationships must be modified in modelling exercises, otherwise once can argue that modelling outcomes are likely to be biased (84). The development of alternative baselines can be critical in ascertaining different institutional and also behavioural changes if relationships change under different policy scenarios and levels of uncertainty. Having alternative counterfactuals can be critical in ascertaining the robustness and sensitivity of the modelling outcomes to the assumptions and limitations embedded in different counterfactuals; such as in the evaluation of the SO_2 cap-and-trade programme in the US (110, 111).

The traditional but narrow single-criterion evaluation approach based on cost-effectiveness; notably in the case of optimisation models, seems to dominate evaluation studies – cf. (51, 59). However, it is argued that the cost-effectiveness criterion is inappropriate to comprehensively address the attributes of energy (efficiency) policy instruments and the institutional and market conditions in which they work (112, 113). Research shows that multiple attributes are related to or can be attached to energy efficiency policy instruments (15, 31, 35). The case for more evaluation criteria (e.g. distributional equity, dynamic efficiency, political feasibility) is further justified when policy instruments explicitly address multiple policy objectives (social, environmental, economical and technical). In fact, we very often see that one policy objective can be maximised only at the expense of others. Conflicting policy objectives can arise in the interplay of energy and other public policy fields. Thus, a multi-criteria evaluation framework can give the opportunity to better comprehend the complexity of the instruments" effects and to identify inevitable policy trade-offs. Furthermore, a multi-criteria evaluation policy framework can allow us to better understand the broad effects, attributes and complexities of energy efficiency policy instruments.

Another research area that can further improve modelling tools is the accounting and order of magnitude of administrative costs borne. Supported by ex-post evaluation, attention must be given to the costs borne by public authorities to implement, monitor and enforce policy instruments (114, 115). Such costs can be related to the design features of the instrument and policy objectives, and to the human and financial resources incurred by the authority administering the instrument with regard to the internal response to implementation. Administrative costs do matter in policy design and instrument choice; however they are often overlooked in evaluation studies and none of the reviewed case studies considered this critical issue. Ignoring such costs can generate biases towards the evaluation and choice of policy options (115). Administrative costs are likely to be a function of the complexity of the institutional framework, the number of regulated firms or subject participants, and the accessibility of necessary data about these firms (116).

6. Conclusions

The literature stresses the need to continuously scrutinize the capability of the modelling tools in relation to the policy evaluation questions. The review confirms that models and corresponding modelling studies provide valuable policy insights; however the study also confirms some criticism and suggests, from a multidisciplinary perspective, different areas for further improvements. The review stresses that, although imperfectly, well-formulated energy modelling tools provide important frameworks for organising complex and extensive end-use household-related data. Taking into account critical challenges such as household behaviour, methodological aspects, decision-making frameworks, uncertainties and data gaps, the identified research challenges could support a more comprehensive foundation for improving the significance and orientation of energy-economy models and future energy-efficiency modelling exercises. As in any rigorous research work, these aspects have to be further developed, tested, evaluated and scrutinized.

The number of factors influencing households" choices regarding energy efficiency technologies is extensive. Whereas economic factors are used as key determinants for technology choice, a broader variety of determinants need to be taken into account when analysing the process of low/slow adoption of efficient technologies (e.g. design, comfort, brand, functionality, reliability, environmental awareness). Quantitative simulation of household behaviour is yet very limited and complex, but it is nonetheless highly necessary to improve the modelling and evaluation of policies. Even if purely economic parameters to mimic policy instruments are examined in this regard – such as discount rates – there is still a gap between what ex-post analyses show and the values used in modelling exercises. The literature strongly indicates that more research is needed on behavioural aspects driving choices about efficient technologies.

Agent-based modelling (ABM) should be further investigated as a complementary or supportive paradigm to address the complexities of household behaviour and technology choice. This modelling approach addresses the forms in which social structures come into view from complex interactions amongst individuals, and how those structures affect and limit individual behaviour; including feedback processes for the identified social structures (117, 118). Thus, this approach can be of value to tackle the critical issue of heterogeneity (actors and their preferences), the multi-agent decision nature of technology choice, and also the interactions and complexities of household behaviour. ABM approaches have become very popular amongst electricity market modelling studies (117, 119), and lessons from these exercises should be taken as departure points.

The literature emphasises the significance of ex-post policy evaluation to further support model development and modelling studies. Empirical evaluation can feedback not only the design and functioning of policy instruments, but also provide critical information to improve modelling tools in aspects such as achievable impact, the nature and scale of transaction costs, co-benefits of energy efficiency improvements, and magnitude of market and behavioural failures. Ex-post evaluation can also feedback technological diffusion processes assumed in models. Likewise, it can improve our understanding of how a portfolio of policy instruments works in practice and how it could be better represented in modelling studies; providing useful lessons about positive (or negative) feedback mechanisms among instruments (e.g. synergies among building codes and performance standards). Ex-post evaluation can also provide insights about the magnitude of administrative costs. Ex-post evaluation is central to complement and further advance models for ex-ante evaluation and thus generate better knowledge and insights that reshape energy efficiency policy evaluation.

Our analysis highlights that there is no single-best method to evaluate energy efficiency policy instruments for the household sector. Provided that the right model is chosen to answer appropriate policy questions, we suggest that a comprehensive evaluation approach still requires a portfolio of analytical methods and much greater collaboration across disciplines. Even if we use sophisticated energy-economy models, there are inherent complex challenges related to energy efficiency policy to overcome and that demand new foundations for future advancements. Progress in energy efficiency policy modelling studies is unlikely to be made if other parallel improvements do not materialise.

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Summary points

1. Bottom-up energy-economy models are formulated on robust economic and engineering principles that integrate technology costs and performance data. Four types of methodological categories are identified: simulation, optimisation, accounting and hybrid.
2. The complexity of household behaviour, uncertainties, and iterative learning processes related to the adoption of efficient technologies challenge the development of bottom-up energy-economy models and the realistic representation of micro-socio-economic decision-making frameworks. There is the need to continuously verify and validate the capability of models in relation to new emerging data and policy questions.
3. Whereas techno-economic variables are used as key determinants for technology choice in modelling tools, empirical literature shows that a larger variety of relevant social and psychological determinants need to be taken into account when analysing the process of adoption of efficient technologies.
4. Energy efficiency policy modelling studies has traditionally targeted the narrow, albeit challenging area of policy impacts, in terms of energy savings, GHG emission reductions and energy savings costs
5. Market and behavioural failures are often not explicitly addressed in modelling studies. Sometimes the use of implicit discount rates is used to confront this modelling challenge, but this approach is subject to criticism and the debate continues.
6. Most modelling studies focus on regulatory policy instruments (e.g. minimum performance standards) or economically-driven policy instruments (e.g. subsidies); however informative policy instruments (e.g. information campaigns) are identified as being much less modelled.
7. Policy instruments tend to be modelled in an idealistic or oversimplified manner and modelling approaches depart from the critical assumption that policy instruments can be represented using techno-economic criteria as the primary driver for decision-making and corresponding technology choice.
8. In spite of the limitations and uncertainties on decision-making processes for technology choice, market heterogeneity, and policy representation, energy-economy models provide significant guidance for policy formulation related to energy efficiency.

Future issues

1. Because of the growing complexities of energy systems, environmental problems and technology markets, there is a need to exploit the combined capabilities and strengths of the models to advance the understanding of energy (efficiency) policy.
2. Open peer review process of model methodologies and databases; including data quality and related uncertainty, is needed to better evaluate the significance of models and modelling results; with explicit advantages and disadvantages of modelling tools being provided to stakeholders.
3. Clear, explicit and realistic representation of policy instruments; including informative instruments, needs to be developed and introduced in modelling studies.
4. Bottom-up energy-economy models will interface with studies on consumer behaviour of energy-use technologies and energy (efficiency) policy, as much more realism is required for technology choice decision frameworks and corresponding determinants. Behavioural economics, social marketing research and social psychology are important to tackle that research challenge.
5. Expanded use of discrete choice and agent-based models will be significant to develop/support hybrid models that can demonstrate/convert qualitative knowledge about household behaviour into a set of quantitative parameters, and also to address the multi-agent decision nature of energy efficiency technology choice.
6. Empirical research on market and behavioural failures is a key goal to further advance model developments and corresponding modelling studies.
7. Integration of non-energy benefits of efficiency improvements, transaction costs of technology choice and implementation, and administration costs into models and modelling studies is needed to better estimate the market potential for policy-driven efficiency improvements.
8. A comprehensive energy efficiency policy evaluation approach requires a portfolio of analytical methods and much greater collaboration across disciplines. Results from ex-post policy evaluation will be essential to provide relevant information (e.g. market and behavioural failures, transaction costs) to improve models and modelling results.

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Mini-glossary

1. **Behavioural failures**: are decision-making actions by firms and consumers that lead to divergences from utility/profit maximisation goals
2. **Bottom-up energy-economy models**: are disaggregated models of the energy–economy system that entail a meticulous characterisation of present and emerging energy technologies and can simulate in detail alternative technology futures, both on the supply- and demand-side.
3. **Energy efficiency policy**: is the sum of governmental actions and decisions addressing energy conservation and efficiency improvements and their present and future economic, environmental and social implications
4. **Energy service demand**: refers to the delivered benefits of useful energy consumption, such as heating, refrigeration, lighting, cooking, etc., as opposed to the simple provision of units of energy (kWh) as such
5. **Evaluation criteria**: are advocated as a basis for normative judgements about effects of policy instruments, or evaluative standards that are the framework upon which a policy choice is judged and eventually made
6. **Market failures**: are flaws in the market that do not allow efficient or optimal allocation of goods and services; a key building block in neo-classical economics
7. **Policy evaluation**: is an applied area of the discipline of evaluation that mostly focuses on expected effects (ex-ante evaluation) or on empirical results (ex-post evaluation) of policy instruments. Effects can be divided into outcomes (i.e. response to the policy instrument by subject participants) or impacts (i.e. resulting changes generated by outcomes on society and the environment).
8. **Policy instruments**: are the set of governmental actions aiming to drive or affect social change, providing incentives or disincentives and information to subject parties in order to achieve policy objectives and goals

Acronyms list

1. **BUENAS**: Bottom-Up Energy Analysis System
2. **LEAP**: Long-Range Energy Alternatives Planning
3. **MAED**: Model for Analysis of Energy Demand
4. **MARKAL**: Market Allocation model
5. **MESSAGE**: Model of Energy Supply Strategy Alternatives and their General Environmental Impacts
6. **MURE**: Mesures d'Utilisation Rationnelle de l'Energie
7. **NEMS-RSDM**: National Energy Modelling System - Residential Sector Demand Module
8. **NIA**: National Impact Analysis model
9. **PAMS**: Policy Analysis Modelling System
10. **REEPS**: Residential End-Use Energy Planning System

Table 1: Key features of reviewed bottom-up energy modelling tools addressing the household sector

Energy modelling tool	Geographical (institutional) origin	Methodological approach	General structure	Main drivers for energy (service) demand	Household technology representation	Technology choice decision approach	Household energy service coverage	Refer
CIMS is a capital vintage model that tracks the evolution of capital stocks through retirements, retrofits, and new purchases	Canada (Simon Fraser University and M.K. Jaccard Associates)	Simulation, equilibrium	System-module type of model similar to NEMS (see below), composed by (i) macro-economic model, (ii) energy supply and conversion model, (iii) energy demand model, and (iv) a global data structure	Energy service demand is either determined exogenously or as a result of the interplay of the energy supply-demand modules with a simplified macro-economic module, which includes energy price service elasticities	Explicit	Technologies compete on the basis of discounted life cycle cost (LCC), including intangible costs (e.g. comfort level) that reflect revealed and stated consumer and business preferences in relation to specific technologies and time	Space heating, cooling, steam, heating, etc.	(7, 23,
BUENAS focuses on energy efficiency standards and labelling programmes. It takes some components of PAMS, such as uptake of appliances, to analyse policy programmes covering the whole world. It integrates known technological opportunities with the experience gained in terms of end-use demand and forecasting markets for end-use technologies.	USA (Collaborative Labelling and Appliance Standards Program [CLASP], Lawrence Berkeley National Laboratory [LBNL])	Accounting, simulation	Three modules: (i) activity forecast, (ii) unit energy saving potential, and (iii) stock accounting	Different macroeconomic drivers (e.g. household income) are considered to project energy demand growth by end-use and by country/region. This is parameterised by appliance diffusion (i.e. average number of a given appliance per household) model as a function of: (i) household income; (ii) electrification; and (iii) urbanisation. The underlying assumption for forecasted energy demand is that ownership rates in developing countries will reach similar levels observed in developed countries, as the income level of the former reaches the level of the latter	Explicit	User-defined	A wide range of end-use services, including refrigeration, cooling, heating, lighting, etc.	(45, 1
LEAP generates models of energy	USA (Stockholm	Accounting, simulation	It operates at two levels: (i) built-in basic accounting	Two key variables: (i) activity levels and (ii) energy intensity.	Explicit/stylistic (depending on	User-defined	Depending on the specific	(18) (unpub

system analysis, ranging from energy resources, generation, distribution to end-use across the economy. It can be used as a database, for forecasting and as a policy analysis tool. It can also support historical analysis of energy systems and analyse their economic and environmental impact	Environment Institute - Boston Centre)		relationships (e.g. energy demand and supply, atmospheric emissions, electricity transmission); and (ii) additional features that modellers can add, such as market penetration of technologies as a function of prices, income level and policy instruments	For the household sector, the households stock can be used to represent the activity level. When it comes to energy intensity, historical values are calculated as the result of total energy consumption of the household sector divided by the chosen activity level	the specific country/region model)		model energy services to be covered are: cooking, lighting, space heating and cooling, building shells, water heating, etc.	inform
MAED provides a methodical accounting framework for evaluating the effect on final energy demand as a result of changes in the technological and socio-economic system	France/Austria (University of Grenoble; International Atomic Energy Agency [IAEA])	Accounting	Based on two modules: (i) MAED_D addresses the economic sectors, sub-sectors and end-use activities included in the model. It computes all the information involved in the scenarios and calculates the total energy demand for the analysed period. (ii) MAED_EL is used to determine the total electric power demand for each hour of the year (i.e. hourly electric load). This module uses the total annual final demand of electricity for each sector as calculated in MAED_D	Final energy demand is forecasted based on medium to long-term development scenarios which are driven by socio-economic, technological and demographic determining factors. MAED-2 (the latest version) allows the modeller to enlarge the pre-defined energy demand structure according to needs and/or data availability	Explicit	User defined and driven by socio-economic and demographic factors	Space heating, water heating, cooking, air conditioning and cooling	(27)
MARKAL is a dynamic linear programming model generator that processes dataset(s) that describe a given energy system. It generates a partial economic equilibrium	OECD-IEA	Optimisation, equilibrium	A user-defined 'Reference Energy System' depicts a network of energy sources, conversion and process technologies (including transmission), energy carriers, demand technologies and end-use sectors (e.g. household, industrial, transportation,	Exogenous projections of energy service demands are set, usually based on economic and demographic projections. Depending on the energy model under analysis, the housing stock is usually the main driver to estimate such exogenous service demands (e.g. SAGE	Explicit	Least-cost combination set of technologies that meet exogenous energy service demands and other (user-defined) constraints	Very comprehensive. For instance, cooling, clothes drying-washing, dishwashing, space-heating, cooking,	(20, 12

model that relies on detailed input to represent global, national, or regional energy systems and their evolution			agricultural, commercial)	project)			lighting, refrigeration, etc	
MESSAGE is an optimisation model that addresses primarily the energy supply sector and its economic and environmental impact	Austria (International Institute for Applied Systems Analysis)	Optimisation, equilibrium	Similar to MARKAL, the model computes all primary energy supply flows that match useful energy demand. This optimisation process is subject to user-defined constraints, such as availability of primary energy resources, evolution of energy conversion technologies and a set of useful energy demand in different end-use sectors	Exogenous projections of energy are set for the all end-use sectors using a separate spreadsheet model called 'Scenario Generator' (SG). The SG is used to convert quantitative assumptions related to the development of the overall final energy intensity. It combines historical energy and economic data with empirically estimated equations of energy demand trends to determine structural change	Stylistic	Least-cost combination set of technologies that meet exogenous energy service demands and other (user-defined) constraints	n/a	(122, 1
MURE allows the analysis and development of rational use of energy scenarios. It aims at estimating potential impacts and costs related to the implementation of policy-driven efficient technologies	EU (SAVE project)	Accounting	It encompasses three main components: (i) MURE entails a database of rational use of energy (RUE) measures documented for 15 EU countries and Norway, addressing several end-use sectors, namely, household, transport, industrial and commercial sectors; (ii) quantitative database that describes the energy system of each country for a base year on a sectoral bottom-up basis level, and (iii) an accounting modelling tool	Driven by the household stock growth rate. The household stock is split into two categories: (i) individual (i.e. single family); and (ii) collective (i.e. multi-family dwelling with four floors and four flats on each floor). Then, the stock of dwellings is also split in three sub-categories in terms of age, with variations according to countries and, in particular, heating needs.	Explicit	User-defined	Energy services are not explicitly addressed, but end-use is disaggregated in different technology levels on a country basis	(26)
NEMS is an integrated energy-economy model that provides projections of US domestic	USA (DOE-EIA)	Simulation, equilibrium optimisation (depending on the block-	Six main block-modules: (i) supply modules (i.e. oil and gas, natural gas transmission and distribution, coal market, renewable fuels modules); (ii)	Household stock and its geographic location are key drivers. The latter is a critical factor that determines consumption values of space	Explicit	A logistic function allocates market shares for competing technologies within each end-use service	Very comprehensive, including sixteen categories:	(21, 22

energy-economy markets in the long term (2030). It is used by DOE to produce the Annual Energy Outlook.		module, e.g. electricity is based on cost-minimisation)	conversion modules (electricity market and petroleum market modules); (iii) demand modules (transportation, commercial, industrial and residential); (iv) a macroeconomic module (i.e. to simulate energy/economy interactions; (v) international energy module (i.e. to simulate world energy/domestic energy interactions; and (vi) an integrating model that contains the mechanisms to compute a general market equilibrium among all the modules	heating. For the household as such, three types of housing are represented: (i) single-family homes; (ii) multi-family homes; and (iii) mobile homes. The Residential Sector Demand Module (RSDM) forecasts energy demand by housing, energy service, fuel and different geographical areas		based on the relative weights of capital and operating costs, annually discounted	space heating, space cooling, clothes washers, dishwashers, water heating, cooking, clothes drying, refrigeration, freezing, etc.	
NIA is used to develop and assess the impacts of new minimum performance standards for specific product types, such as residential appliances, in the US. It generates national energy savings and the net present value (NPV) of efficiency standards of total consumers	USA (DOE-Energy Efficiency and Renewable Energy office)	Accounting	Self-contained Excel spreadsheets that is part of and supported by a wider analytical framework composed of the following tools: (i) market and technology assessment, (ii) life-cycle costs (LCC), (iii) engineering analysis and (iv) shipments analysis.	National energy savings are estimated as the difference between national energy consumption of the product stock, using average unit energy consumption (UEC) of the stock in the base case (i.e. scenario without minimum standards), and the national consumption in the policy case (i.e. scenario with minimum standards). The product stock depends on the number of sales (or shipments) in past years and a survival function. Technology shipments are forecasted as a function of the capital costs and also driven by fuel costs and the projected housing stock	Explicit	User-defined supported by a shipment-elastic model	Depending on the type of technology under analysis, energy service covered include, for instance, space heating, lighting and cooling	(124)

PAMS aims to provide an 'easy-to-use' modelling tool to support policymakers, in particular those from developing countries, in estimating and evaluating costs and benefits of minimum energy performance standards	USA (CLASP, LBNL)	Accounting, simulation	Self-contained Excel spreadsheet that analyses energy consumption and efficiency improvements at (i) household level and (ii) aggregate national level. At household level, PAMS examines the impact of performance standards by looking at costs and benefits based on life-cycle costs (LCC) calculations, taking into account capital and operating costs. At national level, PAMS forecasts total costs and benefits of the consumer market	Total energy demand of the technology/product stock is the product of two factors: (i) unit energy consumption (with and without minimum performance standards); and (ii) the total technology stock – understood as the number of equipment vintage remaining in each year. To determine the technology stock, critical inputs in PAMS are: (i) ownerships estimates; and (ii) shipments, or sales	Explicit	User-defined and supported by a shipment model		(125)
PRIMES simulates a market equilibrium solution for energy supply and demand within each of the 27 EU member states and seven other European countries. It determines an optimal solution by finding the prices of each energy fuel that match the supply and demand of energy	Greece (National Technical University of Athens)	Optimisation, equilibrium	Key modules are (i) different fuel supply (i.e. oil products, fossil gas, coal, electricity and heat production, the so-called 'sub-system'), (ii) energy conversion technologies, (iii) end-use demand sectors, (iv) end-use technologies. These modules interact through the exchange of fuel quantities and prices.	An essential assumption is that producers and consumers of energy respond to changes in fuel prices. Energy demand is a function of energy prices, and commonly evaluated at an EU national level. Critical data for household energy consumption are: (i) household income; (ii) household size; (iii) population; (iv) household stock; and (v) discount rate	Explicit	Based on a total 'perceived cost' which is a function of capital, maintenance and fuel (operating) costs of the equipment, as well as of the household's income	Depending on the categories of dwellings (e.g. central boiler household, electric heating household) the model structures end-use and corresponding energy services in: space heating, cooking, water heating, and air conditioning	(24, 2
REEPS: It allows the evaluation of future energy consumption trends in the household sector under various user-defined assumptions and/or for different	USA (EPRI Consulting)	Simulation	Six modules: (i) exogenous inputs (e.g. fuel prices, household income), (ii) housing stock inputs, (iii) end-use technology inputs (e.g. ownership, efficiency, size, price), (iv) thermal shell inputs (e.g. heat gains/losses, floor	Driven by two important input data sets: (i) exogenous input variables; and (ii) housing stocks input variables. Exogenous input variables include fuel prices, availability of technologies and household size. This input data set is used	Explicit	Based on four decision models: (i) ownership model, (ii) efficiency-choice model (iii) usage model, and (iv) equipment size model.	Space heating, water heating, central air conditioning, room air conditioning, cooking, dishwashing,	(44, 1

policy scenarios.	area), (v) resulting specific end-use models for demand technologies based on input data, and (vi) forecasting outputs (e.g. energy consumption, stock, ownership, purchases)	to forecast the overall macroeconomic conditions in which energy and technology-related forecasts take place. For the housing stock inputs, variables include for instance, housing stock; vintage blocks (i.e. houses existing in a given year versus houses built after that given year); decay rates (i.e. rate at which houses are removed from the housing stock); household size; and household income.		and lighting

Table 2: Key technology choice determinants for household efficient technologies found in ex-post studies

Category	Type of technology	Key determinants	References
Building envelop	Loft and wall insulation, triple/double windows, heating and cooling equipment	Comfort, reduction of noise, purchase and operating costs, aesthetic appearance, timing of decision, income level	(32, 129-132)
Lighting	Compact fluorescent light (CFL) bulbs	Design, aesthetics, availability, compatibility, performance, safety, quality, purchase and operating costs	(39, 133-136)
Appliances	Refrigerators/freezers, dishwashers, washing machines, dryers	Size, brand (seen as a guarantee for quality), purchase costs, income level	(103, 104, 137, 138)

Table 3: Reviewed case studies addressing energy efficiency policy and the household sector[a]

Energy modelling tool	Policy instruments analysed	Geographical focus	Key 'policy handles' in the model used to mimic policy instrument(s)	Are (implicit) discount rates used in the model? If so, to what level?	Reference(s
CIMS	Subsidies for home retrofits and high efficiency heating systems	Canada	'Subsidy attribute' addressing capital and operating costs	20% for home renovation and 9% for heating system	(23)
LEAP	DSM and IRP programmes (e.g. labelling, audits, technology transfer, financial incentives) targeting household appliances	Ecuador	Exogenously determined market penetration rates of different household efficient technologies (e.g. solar water heaters, heat pumps, CFL); fuel substitution (e.g. firewood replaced by LPG) and higher efficiency rates (relative to the baseline)	10% for a cost-benefit analysis derived from the modelling work	(46)
LEAP	Subsidy removal (on kerosene); subsidies on biogas, solar water heater and solar cooker; energy labelling and performance standards for household appliances	India	Technological efficiency improvements for numerous end-use devices (e.g. air conditioners, refrigerators, heaters); including assumed 'moderate' market penetration rates for efficient technologies combined with fuel substitution (e.g. households using dung cakes for cooking and water heating use biogas) and higher market penetration of small-scale renewable energy technologies (e.g. solar water heater, solar cooker, biogas plants).	n/a	(47)
LEAP	Minimum performance standards and labelling on household appliances, building codes, energy management training and awareness raising campaigns	China	Several energy efficiency improvements for numerous end-use devices (HVAC systems) so a lower heating and cooling load are used. Assumed high market penetration rates and greater availability of energy saving devices/appliances (e.g. air conditioners). Standard (or inefficient) devices/appliances are phased out (e.g. air conditioners). 'Upper	n/a	(53)

			bounds' of energy consumption are imposed in order to meet exogenously-determined energy reduction targets (i.e. forcing the model to choose efficient technologies).		
MARKAL	Energy consumption cap and CO_2 emission targets	Switzerland	User-defined constraints are set primary energy per capita consumption and emission levels. For the household sector, the focus is on heating	3% for the baseline scenario	(48)
MARKAL	EU-wide Tradable 'White Certificate' scheme	EU-15 + Iceland, Norway and Switzerland	User-defined energy saving targets; exogenously determined market penetration rates for eligible efficient technologies; different discount rates	30% for baseline and 10% for all eligible and efficient technologies once scheme is modelled	(55)
MARKAL	CO_2 emission reduction targets	UK	User-defined constraints are set on emission levels.	25% rate for conservation measures and advanced technologies. However, a high discount rate is not used explicitly for the modelling market barriers but as a way to capture non-cost driven technology choice-determinants.	(49)
MARKAL	DSM measures, including different energy labelling classes for cloth washing, drying machines, refrigerators, freezers and dish washers (including A to E consumption classes)	Croatia	Technical and economic parameters (e.g. efficiency ratio, capacity level, investment costs, O&M cost, lifetime, initial year of deployment, emission factors). Technology stocks and higher market penetration rates are also used based on expert judgement. Energy consumption classes of household technologies (A to E) are differentiated according to the parameters listed above	15% for space and water heating; 20% for electric appliances for base case. These values are then lowered until technologies are part of optimal set of technologies (i.e. efficiency scenarios)	(54)
REEPS	Minimum efficiency standards based on	USA	Heating and cooling technological parameters	10% was assumed for the	(44)

	the 90-75 American Association of Heating, Refrigeration, and Air Conditioning Engineers (ASHARE) voluntary thermal designs		(e.g. r-value ceiling insulation, r-value wall insulation, reduction in heating design temperature differential) are used for improved efficiency rates compared to the baseline scenario	purpose of modelling trade-offs between initial equipment and annual operating costs. A sensitivity analysis using different values (0, 1, 2, 5 and 10%) was undertaken for the additional energy-saving investment induced by efficiency standards.	
REEPS	No policy instruments as such are explicitly modelled. Instead, the modelling exercise analyses current and projected future energy use by end-use and fuel for the US residential sector. Exogenous inputs for baseline development include minimum efficiency performance standards.	USA	n/a	(i) Ownership model: 20% discount rate for HVAC technologies and 40% for refrigerators, freezers and dryers. (ii) Efficiency choice model: 20% for HVAC equipment decisions	(128)
MURE	Building codes, minimum performance standards and product labelling for heating equipment and household appliances	Germany	Lower energy consumption values of end-use devices, higher market penetration rates, phase of equipment replacement and also higher building stock involvement	No explicit information. However, a default value of 6% annual interest rate is found when reviewing Germany's profile in the 'Data Management' component of the tool	(80)
MURE	Building codes, minimum performance standards and product labelling for heating equipment and household appliances	Italy	Lower energy consumption values of end-use devices, higher market penetration rates, phase of equipment replacement and also higher building stock involvement	No explicit information. However, a default value of 6.4% annual interest rate is found when reviewing Italy's profile in the 'Data Management' component of the tool	(81)
MURE	Building codes, minimum performance standards and product labelling for	UK	Lower energy consumption values of end-use devices, higher market penetration rates,	No explicit information. However, a default value	(82)

	heating equipment and household appliances		phase of equipment replacement and also higher building stock involvement	of 11.6% annual interest rate is found when reviewing UK's profile in the 'Data Management' component of the tool	
NEMS	Tax credits foe efficient technologies (e.g. electric heat pumps and air conditioners)	USA	Capital costs of efficient technologies and higher market shares. The consumer response to the tax rebate and resulting shipments is divided into three components: (i) the 'announcement effect', which represents the consumer response to the tax rebate, independent of the rebate level; (ii) the 'direct price effect', which represents the consumer response to the rebate level as such; and (iii) a 'progress ratio' (or so-called 'increased production experience effect') of 20% (based on experience curves) is used to forecast decreases in future capital costs	No discount rates are used. All cumulative costs are net present-value	(83, 84)
NEMS	Tax credits for building upgrades, installation of new equipment and appliances; minimum performance standards (e.g. furnaces, furnace fans, torchiere lamps, ceiling fan light kits) and building codes	USA	(i) For tax credits: through cost-based equipment choice approach (reduction in capital costs). (ii) For appliance performance standards: through specific assumptions by equipment or end-use (e.g. high efficiency ratios). (iii) For building codes: through specific assumptions by end-use (e.g. adoption of ASHARE 90.1 codes) – similar to the approach used by Cowing and McFadden (1984) with REEPS	The default discount rate applied in NEMS to calculate LCC is 20%	(65)
NIA	Minimum energy efficiency performance standards for residential furnaces and boilers	USA	Technological efficiency improvements (relative to the baseline model equipment[s]), capital costs (including installation costs), operational costs (including maintenance costs) that is cost-efficiency relationships that represent the costs of meeting the	3% and 7% discount rates are used to calculate net present value (NPV) of total consumer LCC savings	(124)

			standards. The 'shipment model' forecasts market shares (or adoption rates) by product class		
NIA	Minimum energy efficiency performance standards for clothes washers	USA	Technical parameters (e.g. efficiency ratios). Economic variables/parameters (i.e. capital, operating costs, and market discount rates) are also considered to develop cost-efficiency relationships to show manufacturer costs of meeting increased efficiency. Market shares by product class (or adoption rates) were forecasted with an 'Accounting Model' (i.e. revised version of the shipment model) that projects annual clothes washer shipments	7% discount rate is used to calculate NPV of total consumer LCC savings (energy and water). A 75% discount rate was used to adjust the relative size of the price and operating savings coefficients for the logit purchase probability model, which is used to support the forecast of shipments (i.e. a purchase consumer model is used to describe consumer decisions)	(139)
PAMS	Minimum energy efficiency performance standards for refrigerators	Central America	Technical parameters are modified that reflects the cost-efficiency relationships for meeting the standard. Design engineering parameters from Brazil are chosen (including baseline model). Efficiency improvements increase as more features to the baseline refrigerator model are added increasing efficiency ratios. Retail price increase resulting from each design option. In the absence of forecasted refrigerator sales, the default shipment model was used, which is based on projected ownership levels	10% discount rate for LCC calculations at the consumer level. A societal discount rate for the aggregate national level and corresponding NPV is not explicitly mentioned; however, the model has a default value of 10%	(140)
PAMS	Labelling endorsement programme for colour TVs	India	'Definite Efficiency Level Target' option was used to determine the efficiency endorsement levels. Label is set at a specific efficiency-technology level regardless of the market	n/a	(57)

			satisfying the efficiency level at the start of the labelling programme (by 2010). Market share of qualified products increases by 25% over a five-year period from the implementation date of the labelling programme. Other parameters: annual colour TV growth rate; technology stock; and the growth rate of electricity prices.		
PAMS	Minimum energy efficiency performance standards for refrigerators	Ghana	Similar to McNeil et al. (2006) for the case of Central America	11.6% discount rate for LCC calculations at the consumer level and a societal discount rate of 10% for the aggregate national level is used	(56)
BUENAS	Minimum energy efficiency performance standards and labelling endorsement for appliances, lighting, and HVAC equipment	Global	Technical parameters (i.e. efficiency targets) for each technology subject to the policy measure(s). Assumptions about efficiency targets based upon expert judgments addressing every region and for every end-use under analysis. Expert knowledge is also used to determine likely adoption targets.	n/a	(45, 120)
MAED	A variety of policy instruments are assumed, such as performance standards and labelling for appliances and support for micro renewable energy technologies)	Syria	Technical efficiency improvements, in the range of 5-10% relative to the base case, combined with higher assumed market penetration rates for efficient electric equipments	n/a	(79)

[a] Whereas the household sector was the main end-use sector under analysis in most of the reviewed cases, note that some studies also address other sectors (e.g. commercial). Table 3 attempts to highlight aspects in relation to the household sector only.

Table 4: Potential portfolio of energy efficiency policy instruments targeting the household sector

Type of policy instrument	Example of policy instrument	Examples of countries where implemented [a]	Specific country example
Economic, financial and market-based instruments: provide incentives or disincentives that alter the economic conditions of subject target participants. New economic/financial conditions aim to trigger (or prevent) the change targeted by the instrument (e.g. retrofitting).	Taxes (reductions/credits/exemptions)	Austria, Belgium, France, Japan, Luxemburg, Norway, Portugal, Sweden, USA	Portuguese taxation programme on less efficient light bulbs
	Subsidies/grants	Australia, Austria, Belgium (Wallonia), Canada, Finland, Germany, Hungary, Ireland, New Zealand, Spain, UK	Finish energy-efficient grant for residential building renovation
	Tradable certificates	Australia, Italy, France	Italian tradable 'White Certificate' scheme
	Soft loans	Australia, Austria, France, Germany, Hungary, Japan, Luxemburg	German (KfW) preferential loans for housing modernization programme
	Rebates	Austria, Italy, Netherlands, Portugal, UK	British 'Warm Front' scheme
	Third party financing	Austria, Germany, Italy, Japan, Netherlands	Austrian financial support (Bürges Förderungsbank) for building energy efficient investments
Regulatory approaches: refer to measures that involve the mandatory fulfilment of aspects by targeted participants. Through legislation, public authorities formulate laws that oblige various groups in society to attain certain targets or renounce to perform certain activities	Performance standards	Australia, Canada, European Union, Japan, Norway	EU minimum energy performance standards for household appliances
	Building codes	Canada, European Union, New Zealand, USA	EU Directive on energy performance in buildings
	Labelling/certification programmes	Australia, European Union, Japan, Mexico, USA	EU energy labelling of household appliances
Informative and voluntary	Awareness raising campaigns	Australia, Austria, Canada, Sweden,	British Energy Saving Trust

schemes: work through the provision of information or knowledge as crucial components in accomplishing or preventing social change, with voluntary actions or policy initiatives originating in the market itself and/or mutually agreed between the government and subject participants		UK, USA	campaign on energy efficiency: 'Save energy, money and environment'
	Energy (audit) management	Austria, France, Germany, Italy, New Zealand, Sweden	Swedish programme on energy-climate community advisers
	Voluntary certification/labelling	Brazil, France, Germany, New Zealand, Switzerland, USA	US Energy Star Label programme
	Voluntary agreements	Australia, Austria, Canada, Finland, Japan, Luxemburg, Netherlands, USA	Dutch 'More with Less' programme

[a] Sources: (15, 141)