energies

MDPI

Article

The Multiple Benefits of the 2030 EU Energy Efficiency Potential

Johannes Thema [1,*], Felix Suerkemper [1], Johan Couder [2], Nora Mzavanadze [3], Souran Chatterjee [4], Jens Teubler [1], Stefan Thomas [1], Diana Ürge-Vorsatz [4], Martin Bo Hansen [5], Stefan Bouzarovski [3], Jana Rasch [1] and Sabine Wilke [5]

[1] Wuppertal Institute for Climate, Environment and Energy, Döppersberg 19, 42103 Wuppertal, Germany
[2] Department of Engineering Management, University of Antwerp, Prinsstraat 13, 2000 Antwerpen, Belgium
[3] School of Environment, Education and Development, University of Manchester, Oxford Road, Manchester M13 9PL, UK
[4] Centre for Climate Change and Sustainable Energy Policy, Central European University, Nádor u. 9, 1051 Budapest, Hungary
[5] Copenhagen Economics, Langebrogade 1B, 1411 Copenhagen, Denmark
* Correspondence: johannes.thema@wupperinst.org; Tel.: +49-(0)202-249-2186

Received: 11 June 2019; Accepted: 17 July 2019; Published: 20 July 2019

check for updates

Abstract: The implementation of energy efficiency improvement actions not only yields energy and greenhouse gas emission savings, but also leads to other multiple impacts such as air pollution reductions and subsequent health and eco-system effects, resource impacts, economic effects on labour markets, aggregate demand and energy prices or on energy security. While many of these impacts have been studied in previous research, this work quantifies them in one consistent framework based on a common underlying bottom-up funded energy efficiency scenario across the EU. These scenario data are used to quantify multiple impacts by energy efficiency improvement action and for all EU28 member states using existing approaches and partially further developing methodologies. Where possible, impacts are integrated into cost-benefit analyses. We find that with a conservative estimate, multiple impacts sum up to a size of at least 50% of energy cost savings, with substantial impacts coming from e.g., air pollution, energy poverty reduction and economic impacts.

Keywords: energy efficiency; cost-benefit analysis; impact assessment; multiple benefits; air pollutants; energy security; macro-economy; resources; fuel poverty

1. Introduction and Previous Studies

1.1. Multiple Impacts of Energy Efficiency

Energy efficiency improvement (EEI) is not an end in itself but a means to address major political challenges such as climate change mitigation, energy security, and health damages resulting from air pollution or economic downturns. The adoption of the energy efficiency first principle in European legislation in the Energy Efficiency Directive [1] in 2012, emphasised the relevance of multiple impacts (MI) in policy-making and reflects their motivation for European policy action, but in political and institutional discourses and negotiations, they are seldom used as key arguments. The reason for this may be the often very complex and indirect causal link from investments in EEI to their impacts, and time lags in visible impacts.

Research findings on these links are disperse and vary widely with regard to the magnitudes of the impacts and with significant gaps in the coverage of sectors, technologies, geography. Moreover, many impacts are often not quantified and monetised and sometimes even not identified by decision-makers and affected stakeholders [2]. In recent years, research on wider benefits from energy efficiency improvements for the economy, society and end-users has expanded rapidly. These impacts are often analysed in isolation, but together build an entire new research field with hundreds of publications.

The assessment methods of air pollution co-benefits in the literature depends on several factors: (1) geographical scope, (2) emitting sectors assessed (point sources versus non-point sources); (3) energy supply input data - especially its level of detail; (4) air pollution receptors considered (human health, ecosystems, forests, agricultural harvests). Researchers often recur on existing models-from a variety of models available for specific sectors/recipients/types of pollutants (e.g., TREMOVE [3] or DO3SE [4]) to whole-economy models (e.g., GAINS [5]). In the absence of detailed energy input data and/or access to complex modelling tools, researchers often apply so called marginal co-benefit estimates (e.g., ExternE project estimates per country and type of pollutant and pollution source [6]). The impact pathway framework and methodology [6], pioneered in 1990s, remains to be at the core of all kinds of air pollution (avoided) damage assessments. For an extensive overview on air pollution and resulting human health and ecological impacts see [7].

Analysis of material resource impacts is a widely established research field and of high political relevance in the EU [8]. Resources can be disaggregated [9], and for studies looking at resource use of energy efficiency, a focus on raw materials and their sub-types seems appropriate [10]. An assessment method for scarcity and economic value of raw materials is proposed by [11], but this does not cover environmental impacts. For this, typically life-cycle assessment (LCA) methods are applied. Respective guidelines [12] are available and a handbook provides further guidance and quality assurance [13]. In addition, frequently applied methods include material flow (MFA) accounting, in which economy is a subsystem within the environment. Resources are extracted from nature as inputs, transformed (e.g., to products or useful energy) and re-enter the nature as outputs (e.g., as emissions or waste). Ref. [14] describe the basic model, while accounting and methodological guidelines have been set by EUROSTAT [15,16].

Although energy poverty as a concept dates back to the early 1990s [17], rarely did social welfare aspects enter social cost-benefit analyses of climate mitigation activities in the housing sector. Energy poverty-related co-benefits have been conceptualized, assessed and monetized in two ex-ante national-level assessments modelling costs and benefits of national housing stock renovation: (1) Ireland (study completed in 1999 [18], applied to cost-benefit analysis [19] and introduced to modelling [20]) and (2) Hungary (study completed in 2013 [21]). The case of Ireland assesses morbidity, mortality and comfort co-benefits, while the case of Hungary assesses only mortality and comfort. Due to the geographical scale of assessment and data availability only mortality effects due to indoor cold exposure have been assessed. However, asthma morbidity effect has modelled for the 1st time in such type of studies. For an encompassing discussion of related literature see [22].

The impact of energy efficiency on labour productivity has been studied e.g., through surveys in commercial buildings [23], findings of a meta-study on the effects of indoor temperatures on health and productivity are presented in [24]. Ref. [25] first included these effects into cost-benefit analysis and showed how a marginal energy savings cost curve is altered if impacts are included.

Economic impacts have been analysed in many previous studies, such as the latest EU Commission impact assessments for the EED revision [26] or a dedicated commissioned study [27]. The standard approach for estimating short-term economic impacts is input-output modelling [28], following impacts on tax revenues largely done by using keynesian multipliers and budgetary semi-elasticities [29]. Short-term impacts are discussed as only expectable if output gaps exist. The problem with estimating them for a point in time in the farther future is the uncertainty of these output gaps [30]. Naess-Schmidt et al. [31] discuss approaches of economic modelling in detail, also covering general equilibrium models for long-term impact and price effect estimations.

Energy dependency has been operationalised to indicators and applied to EU countries [32], energy security indicators presented in [33]. Energy systems, their stability, reliability and security have a track record of accounting and simulation in models such as ENPEP-BALANCE [34], the

Energy Transition Model (ETM) [35], Poles [36], EnergyPLAN [37] and LEAP (6) (for the software see [38]), aiming to match available energy-related resources and technologies to energy demand. Basic inputs include detailed, per member-state EU base-year energy statistics covering production and consumption levels, as well as projected energy demand growth and relevant policy and technical constraints. An encompassing literature overview is given by Couder [39].

Early reports quantified specific impacts for certain sectors, e.g., the buildings sector [40]. In recent years, efforts to quantify MI at the European level have increased. In 2014, the IEA published the hallmark book on "Capturing the Multiple Benefits of Energy Efficiency" [41], the first comprehensive collection of knowledge and approaches on their quantification. On a national level, analyses were done, e.g., for Sweden [42] or Thailand [43]. In the frame of the 2016 "Winter Package" of EU energy legislation, the Energy Efficiency Directive (EED) [44] and Energy Performance of Buildings Directive (EPBD 2010/31/EU) have been redrafted. As usual, accompanying impact assessments were done, and in this case now also contain numerous other impacts such as economic (labour market, GDP), energy imports and air pollution with resulting health impacts. In 2017, the EU-Commission published a separate report [27] quantifying additional impacts of EE policy. However, it remains a big task for science and policy to understand causality and size of MI, to be able to put them at the heart of policy decisions.

1.2. Innovations and Approach of the COMBI Project

In 2015, there was an immediate need to integrate the state of knowledge for individual impacts into one consistent approach. The European Horizon 2020 research project COMBI ("Calculating and Operationalizing the Multiple Benefits of Energy Efficiency in Europe") did this by five central research innovations: (1) starting from a common scenario data base with energy savings, potentials and technology costs per EU country for the 21 most important energy efficiency actions in the residential, commercial, industrial and transport sectors, (2) applying or developing adequate methodologies for impact quantification, monetisation and aggregation, (3) applying these methods in order to calculate values for the most important multiple impacts and where adequate, monetising (4) incorporating the derived values into cost-benefit calculations and (5) providing an online visualisation tool for customisable graphical analysis and assessment of multiple impacts and data extraction.

This research analyses multiple impacts from EE from an overarching societal perspective, including as many impacts as possible. Primary guidance on indicators for consideration has been sought in the Green Economy literature [45], the IEA contribution on Multiple Benefits [41] or the European Commission impact assessment [26] and special report [15]. The impacts were operationalised to indicators that are possible to quantify. The choice of indicators is on the other hand limited by data availability and sufficient evidence from existing research that can be translated to quantification approaches.

The COMBI research resulted with a total of 32 impact indicators covering the categories of air pollution (with ecosystems and human health impacts), resource impacts (fossil fuels, metals, minerals, biotic materials and unused extraction and carbon footprint), energy poverty (human health) and productivity, macro-economic impacts (aggregate demand/GDP, employment, energy price effects) and energy system impacts (security and system impacts). For the full list of indicators see e.g., Thema and Rasch [46].

1.3. Aim and Structure of the Paper

The objective of this paper is to summarise and discuss the COMBI approach and methodologies, the most critical challenges, the core results in terms of quantified and monetised impacts. The paper concludes with a short summary, why MI evaluation is necessary for policy-making.

2. Materials and Methods

2.1. Quantification and Monetisation

Joint research efforts provide estimates of the major multiple impacts in the year 2030 that result from energy efficiency investments that are additional to a reference scenario. This means results depict additional multiple impacts of more ambitious policy action. All existing energy efficiency policies are thus already considered in the reference scenario, the efficiency scenario assumes technology implementation following from more ambitious policies. The difference between the baseline and efficiency scenario is then used as input data (i.e., additional energy savings and investment costs) for quantifying additional multiple impacts in 2030. The ambition (amount of energy savings vs. the reference scenario of around 8%) of the COMBI EE-scenario is between the EU 33% and 35% targets (EUCO + 33 to EUCO + 35 EU scenario).

The scenarios are bottom-up funded with 21 energy efficiency improvement (EEI) actions in the buildings, transport and industry sectors (see Table 1). For the selection process and description of individual EEI actions see Couder [47], for additional details [48]. These actions are implemented in high-resolution stock models to quantify energy savings and investment costs. Impacts are quantified by EU member state and by single energy efficiency improvement action.

Table 1. End-use EEI actions of the COMBI project.

#	End-Use Energy Efficiency ActionImproving Energy Efficiency in or Through:
Action 1	residential refurbishment of the building shell + space heating + ventilation + space cooling (air-conditioning)
Action 2	residential new dwellings
Action 3	residential lighting (all dwellings)
Action 4	residential cold appliances (all dwellings)
Action 5	non-residential refurbishment of building shell + space heating + ventilation + space cooling (air-conditioning)
Action 6	non-residential new buildings
Action 7	non-residential lighting (all buildings)
Action 8	non-residential product cooling (all buildings)
Action 9	passenger transport—modal shift
Action 10	passenger transport—motorized two-wheelers
Action 11	passenger transport—cars
Action 12	passenger transport—public road/buses
Action 13	freight transport—modal shift
Action 14	freight transport—light duty trucks (LDT)
Action 15	freight transport—heavy duty trucks (HDT)
Action 16	industry —high temperature process heating
Action 17	industry —low and medium temperature process heating
Action 18	industry —process cooling
Action 19	industry —specific process electricity
Action 20	industry —motor drives
Action 21	industry —HVAC in industrial buildings

Source: [46].

To evaluate the size and relevance of impacts, indicators need to be quantified, in either absolute terms or relative changes. Most indicators are of physical nature (with the exception of some economic indicators). In a first step, they are quantified in respective physical units such as tonnes of CO_2 equivalents, tonnes of air pollutants, savings in lost life-years, additional employment in job-years etc. For a comparison and discussion of different policy options and their respective impacts, a comparison of impacts on a physical level can already be of significant added value. This approach is taken e.g., in the EU EED impact assessment [26].

However, in order to perform a cost-benefit analysis (CBA), indicators need to be monetised. For most impacts, established monetisation approaches are available, but in some cases there are ethical concerns or approaches are otherwise controversial, such as with the valuation of life-years (monetisation often includes country-specific income levels leading to country-specific values of lives). For some indicators, monetisation remains a major challenge and their inclusion to CBA is contingent on available methodologies. This is particularly relevant for health-related impacts from air pollution [49], housing [50], resources [51] and productivity [52]. Monetisation is less problematic for economic impacts [53] and energy security [54]. We accept the caveats, but however see the value added in proceeding with monetisation for the sake of better communication of MI importance and direct comparison of different multiple impacts in terms of their sizes, a more detailed discussion can be found in [55]. In total, 17 out of 30 multiple impact indicators were possible to monetise within this research.

In addition, several impacts overlap, which is a challenge to their aggregation. An overarching aggregation methodology has been developed [55] in order to incorporate quantified impacts into the cost-benefit analysis avoiding double counting (see section below on impact synthesis for more details).

2.2. Methods for Multiple Impact Analysis

The COMBI project quantifies 32 different multiple impacts (MI) of energy efficiency improvement (EEI) actions, which require different types of assessment methodologies. Table 2 summarises the quantification methods of the five impact categories, a more detailed overview is included in the Appendix A. The methods are always used for quantifications in the year 2030 and the avoided extent of the respective impact due to accelerated energy efficiency interventions, i.e., the difference between the reference scenario and the COMBI efficiency scenario resulting from 21 energy efficiency improvement actions. The overview on individual methodologies per impact indicator is available in greater detail in the Annex and the synthesis methodology [55]. Details on the respective methodologies for the different impact quantifications are presented in the COMBI quantification reports. The following sections describe brief summaries on applied methodologies per impact category and the impact indicators quantified.

Table 2. Overview of COMBI impact indicators and respective quantification methodologies.

Impact Category	COMBI Quantification Methods
Air pollution	GAINS model
Resources	Material Flow Accounting (MFA) Direct carbon emissions: emission factors for fuel types Carbon Footprint: Life-cycle Assessment of characterised GHG and their global warming potential (GWP) in 100 years (GWP 100a)
Social welfare	COMBI model
Economy	Input/output analysis and fiscal multiplier analysis Budgetary semi-elasticities General equilibrium modelling (Copenhagen Economics Global Climate and Energy Model-CECEM)
Energy system	COMBI energy balance model COMBI power sector model

Source: [46].

2.2.1. Impacts of Reduced Pollution on Health and Eco-Systems

Air pollutants affect human health negatively as they cause acute and chronic diseases. In addition, they cause acidification and eutrophication, which are indicators of ecosystem health. For our research purposes we applied the GAINS model (Greenhouse Gas–Air Pollution Interactions and Synergies model from the IIASA institute) to quantify effects of accelerated energy efficiency improvements. GAINS is by far the most advanced modelling tool for air pollution modelling on a national and regional scale and has been widely used to inform the European Union's air quality policies and negotiations under the United Nations Framework Convention on Climate Change (UNFCCC). The GAINS model in its basic mode can be accessed online; some of its basic features and main scenarios can be explored at [56]. The model contains various modelling layers: air pollution emission modelling, air pollution control modelling, dispersion, deposition and secondary air pollutant modelling, human health and ecosystem health impacts modelling and climate emissions modelling. [5] contains an outline of the EC4MACS project leading to the GAINS model with task descriptions and policy applications of the model. The full causal chain, methodology and model components are laid down in [57].

Impact indicators quantified are air pollution and human health (various indicators), eco-systems acidification and eutrophication. Air pollution emissions (quantification mid-points) are outdoor air pollutants emissions from energy combustion and transportation. Human health gains are measured in premature mortality due to the exposure of different outdoor pollutants. Eco-system acidification is defined as the total ecosystem area spared from acidification. Eco-systems eutrophication refers to the total ecosystem area spared from eutrophication. For more information on the methodology see [49], and specifically on the GAINS model [49] (p. 13).

Only human health impacts have been monetised, since their units are standardized and universally applied in the literature. Monetary estimates can thus directly be applied in terms of Value of a Life Year (VOLY) for avoided premature mortality due to PM2.5 exposure and ground level ozone exposure as well as years of life lost (YOLLs) for avoided life expectancy loss to the surviving population due to PM2.5 exposure.

2.2.2. Resource Impacts: Abiotic and Biotic Materials

For our research purpose, a bottom-up characterisation model of electricity, heat, fuel systems as well as for vehicles and lighting systems in Europe was developed [51]. The model relates energy efficiency savings from the EEI actions in the EU-28 in 2030 to the following impact indicators: (1) Material Footprint in tons–the sum of savings of abiotic (fossil fuels, metal ores, minerals) and biotic (not further specified) raw materials from nature; including raw materials without economic use (unused extraction); (2) Carbon Footprint in tons of CO_2-equivalents (direct and indirect/upstream GHG emission reductions); (3) direct GHG emission reductions in tons of CO_2-equivalents (savings in GHG emissions from combustion of energy carriers/fuels). Characterisation factors for (1) Material and (2) Carbon Footprint are based on the upstream material and energy flows for energy conversion (e.g., power plants) and distribution (e.g., electrical/gas/oil grids). The impacts quantified in this lifecycle (cradle-to-gate) assessment not only occur within EU frontiers, but also outside the EU in energy exporting countries. The impact quantification of (3) Direct GHG emissions is based on fossil fuel combustion for energy use and takes place only within the EU.

The methods applied for indicator quantification are Material Flow Accounting (MFA) and Life Cycle Assessment (LCA). More specifically, we use Material-Input-per-Service (MIPS). For a basic introduction to the concept see [58] (in German), the application [59] and modelling implementation [60]. Political consequences are described in [61] (in German) and results and implications from our resource research published in [62]. Global Warming Potential for 100 years (GWP 100a) is estimated using figures from the International Panel on Climate Change [63], Ecocosts by Voigtländer [64] and material footprint [65].

Two types of models are applied for this research: use-phase models and production-phase models. All outputs relate to the difference between scenarios, i.e., resource savings/additional use. The quantified unit is tons of material or tons of CO_{2eq} per kWh of final energy use or per product.

The use-phase model (cradle-to-gate energy supply) covers all 21 EEI actions in all 28 countries. It consists of (often country-specific) multipliers for all three endpoints listed above and sub-impacts in relation to the final energy demand in both reference and energy efficiency scenario. It is based on supply models for fuels, electricity and heat, which were generated from the input data, EUROSTAT and generic lifecycle inventories (e.g., Ecoinvent 3.1.).

The production-phase models, analyse the resource impacts from the production of EEI action-related technologies and products. They consist of EU-average multipliers for the cradle-to-gate production of product stocks in both scenarios (all endpoints and sub-impacts with exception of direct GHG emissions). There were severe gaps in data availability for many EEI actions. Therefore, the production phases of only few EEI actions was possible to be covered: vehicles for transport and lighting systems for buildings. This severe limitation of available input data indicates substantial future research needs and room for improvement to resource impact quantification. As a consequence, production-phase impacts are severely underestimated in this research effort.

Only fossil fuels use and metal ores from economically used extraction (sub-impacts of the Material Footprint) have been monetised. Other impacts such as the Carbon Footprint could not be monetised due to lack of data or lack of available methods. The monetisation method is based on future eco-costs of raw material depletion. Depletion of scarce materials with further extraction leads to additional investments needs to maintain quality and prevent environmental externalities. This may be quantified using indirect or external material costs for fossil fuels and metals.

2.2.3. Energy Poverty-Related Health Impacts

Social welfare impacts of energy efficiency interventions are relevant mostly in the building and urban transport sectors [22]. The most comprehensive study and database providing insights and data into mortality and morbidity across countries and regions since 1990 is the Global Burden of Disease health monitoring project is lead by the Institute for Health Metrics and Evaluation at the University of Washington [66]. Details on the inception, evolution and future challenges are discussed in [67].

In the residential building sector, the biggest societal gains are to be reaped when energy efficiency interventions target low-income groups, especially those suffering from energy poverty–a condition defined by the inability of a household to secure a socially-and materially-necessitated level of energy services in the home as presented by the IEA [41] and other global reviews [68]. The impact of energy efficiency interventions focuses on energy poverty-related public health conditions. We thus focused on indoor cold and asthma morbidity due to indoor dampness and their effects on winter mortality/morbidity. The standard excess winter deaths formula has been further developed for this research to account for recent methodological criticism–excess cold weather deaths have been quantified instead, accounting not for a pre-defined "winter period", but rather empirical cold weather days. The burden of disease approach was then applied to evaluate the extent of asthma morbidity due to indoor dampness, the detailed method laid down in [50]. The future projections assumed that the annual burden of disease remained constant (ceteris paribus) with the exception of changes in the two factors indoor cold and indoor dampness. Their prevalence is modelled in relation to the extent and type of country-specific changes in the residential housing stock resulting from the underlying stock modelling [48] and contingent on the existence and focus of policies directed towards the vulnerable population. Finally, excess cold weather deaths are monetised applying estimates for the value of a life year (VOLY).

2.2.4. Impacts on Productivity

For the quantification of labour productivity gains, a new methodological framework has been developed to assess three indicators: (1) the number of active days available for productive work, affected e.g., by being sick or stuck in traffic; (2) workforce performance within a certain time frame, which can be increased through improved mental wellbeing of the workforce as a result of better indoor air quality and thermal comfort of tertiary buildings, and (3) working ability/value added per unit of time worked, which is affected e.g., through education increasing productivity/earning ability. Productivity metrics are relevant for two energy efficiency improvement actions: heating, ventilation, air-conditioning system in buildings with airtight building envelope, and modal shift towards active transportation. The quantification builds on stock data from scenario modelling [48] as well as health improvement and congestion reduction factors and data from the literature (for an overview see [52]).

Indicators include active days (impact resulting from asthma, allergy, cardiovascular disease, cold and flu and traffic time saved) and workforce performance. Indoor exposure-related active days are quantified with an indoor dose-response model, congestion-related active days with a basic reduction method, and workforce performance with a basic performance improvement equation [52].

2.2.5. Macroeconomic Impacts: Employment, GDP and Tax Revenues

Macroeconomic effects are assessed in two ways: (1) Short-run business cycle impacts and (2) long-run structural impacts. The main difference between both approaches is that the first analyses the value created through a stimulation of the economy by additional expenditures, the second analyses economic effects over a longer period of time the theoretic stat of equilibrium is assumed to apply.

The specific impact indicators quantified are temporary (business-cycle) aggregate demand and employment, temporary (business-cycle) public budget effects, fossil fuel price effects, ETS price effects, Terms of Trade effect and sectoral shifts. For the quantification of (business-cycle) aggregate demand, employment and public budget effects, methods of input/output analysis and fiscal multiplier analysis are used. The input-output-model allows for the calculation of GDP/employment effects that each EEI action can potentially create and to what extent this boost is 'additional'. It has to be noted that investment spending will only be beneficial (in a short-run macroeconomic sense) if the economy is in a situation where the output gap is negative. An assessment of the size of the output gap over the relevant time period is necessary, however not available for 2030 at this time. Short-term impacts have to be interpreted as "potential impacts, conditional on the existence of an output gap". The fossil fuel- and the ETS price effects as well as the Terms of Trade effect and sectoral shifts are quantified via general equilibrium modelling (Copenhagen Economics Global Climate and Energy Model-CECEM). Methods applied for macro-economic impact estimation are explained in detail in [53].

2.2.6. Impacts on Energy System & Security

The energy supply chain is a highly complex system as is the assessment of its security [38] (p. 336). A set of vulnerability indicators (see e.g., [69]) has been developed, which help to operationalise and assess the security of the European energy system. Model-based scenario analysis helps to assess how various policies put forward by the EU affect energy security [70]. To this end, an energy system model for the EU member states has been developed. This COMBI energy balance model calculates the resulting outputs of the energy transformation sectors (mainly power plants and oil refineries), as well as the required net imports. These outputs are used to construct five main indicators: (1) energy intensity, (2) import dependency (net imports and net import costs), (3) A Herfindahl-Hirschman Index (HHI)-based energy security indicator capturing the effects of energy efficiency actions on import dependency, diversification of energy sources and geographical diversification, (4) power output and avoided costs of power infrastructure comprising the effects of a decrease in electricity demand and (5) de-rated reserve capacity (reserve capacity of the power sector, divided by its total installed capacity), which measures the security of electricity supply and power system reliability.

The energy intensity indicator is a direct result calculated from the final energy demand reduced by COMBI actions divided by GDP. Import dependency is calculated the COMBI energy balance model, with the central input being final energy demand as reduced by EEI actions. The relevant output is net energy imports, for monetisation multiplied by their respective energy prices. For the quantification of aggregated energy security, we also apply the energy balance model. The relevant indicator is net energy imports, weighted by an allocation model reflecting the origin country of imports and risk indicators to assess political risks in these countries. Avoided electric power output and investment costs in power generation infrastructure are also quantified with the energy balance model. By means of a power sector model, the mix of power plant and cogeneration plant technologies and capacities are determined. The indicator used is net power output. Avoided power generation multiplied by specific capital costs per technology results in avoided investment costs as a monetary indicator. To quantify the de-rated reserve capacity rate, again the COMBI energy balance model and power sector model are employed to calculate peak loads and the resulting required reserve capacities based on annual load duration curves. The energy balance model and quantified impacts are explained in detail in [54].

2.3. Impact Synthesis and Cost-Benefit Analysis

If multiple impacts could be consistently included in cost-benefit evaluations of energy efficiency actions, they could significantly alter the results [71]. One important challenge and first pre-condition for multiple impacts to enter CBA is that they can be converted to a common unit, i.e., that they can be monetized. Second, multiple impacts may overlap and interact among each other as laid down early [2]. The issue has drawn intensive attention [41] and ways to avoid them proposed early [71]. The double counting of impacts in CBA must be avoided to yield a reliable and credible CBA estimate. The second precondition is to either adjust impacts for double-counting or if not possible, to include only impacts, where any danger of double-counting can be ruled out. A comprehensive accounting framework for multiple impacts is required to prevent over-or under-estimation in CBA [45]. The proposed impact pathway mapping approach was applied to identify the interactions among the impacts and to understand the causal effects of impacts in a detailed manner and to finally decide whether to rule out interactions, or account for overlaps. Where interactions could not be excluded, respective impacts were not incorporated in the CBA [55]. Finally, 11 out of 17 monetized impacts could be included into the COMBI CBA for which double-counting could be ruled out. The following seven steps were taken to accurately measure and aggregate multiple impacts and include them into CBA:

1. Identification of impacts and explicit root causes
2. Identification of causal effects of an impact i.e., whether the impact results in another impact
3. Selection of significant end-points
4. Quantification of additional impacts in physical units
5. Monetization of physical values where possible
6. Aggregation of impacts
7. Integration of monetised values in cost-benefit analysis (CBA).

The danger of double-counting led us to the exclusion of various monetized impacts from CBA. Among these are resource impacts (as those are at least partially covered by investment costs), aggregate demand and employment effects (it was impossible to determine the fraction already counted with investment costs, mutually overlapping) and public budgets (partially overlapping with investment costs, other economic and health impacts). As economic impacts are among the largest in size, this leads to an underestimation of total multiple impacts within this research. Future work is needed to determine the fractions of these impacts that are additional to others in order to include them in future CBA.

3. Results

3.1. Impacts in Physical Terms

All impacts are quantified by EU28 member states and for each of the 21 EEI actions. All results are available from the project website [72]. As presented above, the main input data used for impact quantifications includes additional annual energy savings (in 2030), resulting energy cost savings and additional investment costs (total cumulated until 2030 and annualised). The implementation of all 21 EEI actions at the level of ambition that was assumed for the EE-scenario would lead in EU28 member states to additional annual energy savings of 1647 TWh/year or 142 Mtoe/year in 2030, additional energy cost savings of 131.15 bn€/year in 2030 and would induce additional (annualised) investments of 94.60 bn€/year. In addition to this energy and investment impacts, we found that quantified multiple impacts are substantial. Table 3 gives an overview on key results of quantified physical impacts for the difference between reference and efficiency scenario, as annual values in the year 2030. The large spread of the energy poverty-related health impacts in the impact category social welfare is due to a sensitivity analysis performed for the case whether policies are targeted directly towards vulnerable households or not.

Table 3. Impacts in physical terms by category (annual values in the year 2030).

Impact Category	COMBI Results	Reference
Air pollution	>10,000 avoided premature deaths due to PM2.5 442 avoided premature deaths due to O3 230,000 YOLLs of avoided life expectancy loss due to PM2.5 362Mt avoided direct CO_{2eq} emissions	[49]
Resources	850 Mt savings of material resources	[51]
Social welfare	3000–24,000 avoided premature deaths due to indoor cold 2700–22,300 avoided DALYs due to indoor dampness related asthma 39 mn additional workdays	[50] [52]
Economy	1% rise in GDP 2.3 mn job-years Decrease in fossil fuel prices: −1.3% oil, −2% coal, −2.9% gas	[53]
Energy system	257 TWh avoided generation of power from combustibles up to 5% improved energy security 0.8%-points lower fossil fuel imports	[54]

Sources: [46] for an overview and right column for detailed references.

The implementation of the 21 EEI actions leads to substantial impacts (figures are per year as of 2030): Throughout Europe, significant air pollution reductions (figures are included in [46] and the online tool for download [72]) lead to over 10,000 premature deaths due to PM2.5 exposure and another over 400 deaths due to ozone exposure can be avoided. In addition, reduced PM2.5 exposure leads to 230,000 less years of life lost. In total, 362 Mt CO_{2eq} of direct GHG emissions can be saved, when including energy supply upstream-emissions, the carbon footprint amounts to over 500 Mt CO_{2eq} [51].

Depending on whether policies are focused towards the vulnerable population or not, between 3000 and 24,000 premature deaths due to indoor cold can be avoided by building improvements with an additional avoided loss of 2700 to 22,300 disability-adjusted life years (DALYs) [50]. Improved health conditions can lead to 39 mn additional productive work-days across the EU [52].

Short-term economic impacts of the 21 EEI actions lead to an additional rise in GDP of up to 1% due to the investment stimulus, resulting in up to 2.3 mn additional job-years and 85 bn € additional tax revenues for public budgets. Prices for fossil fuels decrease by 1.3 (gas) to 2.9% (oil) relative to the reference scenario [53].

The energy efficiency push would lead to a lower energy demand and consequent avoided power generation from combustible-based plants of 257 TWh/year. The estimated impact on the energy security index varies between EU member states from in some cases (Spain, Portugal) negative values (−2%) to in most cases positive values (up to 5%). Imports of fossil fuels would decrease by about 0.8%-points [54].

3.2. Monetised Impacts

In addition to energy savings and induced investment, out of the 30 quantified multiple impacts, 17 were possible to monetize. Figure 1 illustrates all monetised impacts pre-aggregated to 8 impact categories in bn € (colours represent various EEI actions, for the legend see [72]), irrespective of possible double counting. Macroeconomic impacts (here, including only short-term aggregate demand) are highest, followed by energy cost savings and cost savings of material resources. Lowest monetised impacts are reduced mortality as a result of less air pollution and improved labour productivity (additional workdays gained). An important note on health impacts is, that morbidity effects have not been possible to quantify with the applied models but are likely to be substantial.

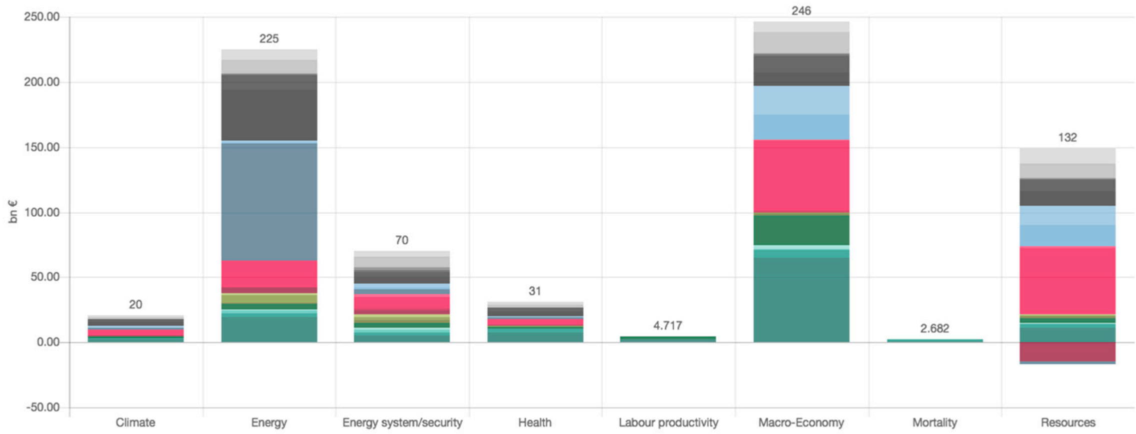

Figure 1. Monetised impacts in bn €/y in 2030 (for colour legend see [72]).

3.3. *Cost-Benefit Analysis*

A central challenge of including a large number of multiple impacts in CBA is to avoid a double counting of impacts as they may overlap with each other, with direct energy cost savings or investment costs. One example is additional aggregate demand/GDP that conceptually includes many other impacts such as health or investment costs. In order to rule out double counting, only 11 out of the 17 monetised impacts were included in the CBA (see section on impact synthesis above).

In addition, as for transport modal shift actions only investment costs for rolling stock were available, but not for infrastructure investments, we decided to exclude these from CBA. Freight road transport, investment costs were out-dated, and these actions are also excluded.

CBA results should be interpreted as a conservative estimate of the cost-effectiveness from a societal perspective, as several of the existing impacts could not be monetized (or even physically quantified); where there was danger of partial double-counting, impacts were excluded and quantification methods mostly are conservative (e.g., not quantifying all impact pathways) and the reference scenario is ambitious since fully complying with current policies.

A variety of cost-benefit indicators are calculated for research purposes, including net present value (life-time and annualised), levelised cost of energy and GHG emissions saved, cost-benefit and benefit-cost ratios and marginal cost curves. Details on indicators and calculation approaches can be found in [73]. Figure 2 shows results as annualised net present value (red thin line) resulting from costs (investments, grey) and benefits (energy cost savings, blue and multiple impacts, colours). The upper graph excludes monetised multiple impacts, the lower graph includes them. EEI actions are cost effective if the annualised net present value (red thin line) is positive, as benefits exceed costs.

The results show that even without MI, most EEI actions are cost-effective according to the stock modelling input data, except for tertiary buildings refurbishment, passenger road transport (car, public transport/buses, two-wheelers). The reason for this is that analysed actions go beyond current policies and legal requirements.

Including MI, almost all EEI actions included become cost-effective, except for cold appliances (analysed action is A+++ only) and two wheelers (costly action, but limited savings potential). Analysis of modal shift was not possible due to no availability of infrastructure investment costs, and freight transport actions due to unreliability of out-dated investment costs.

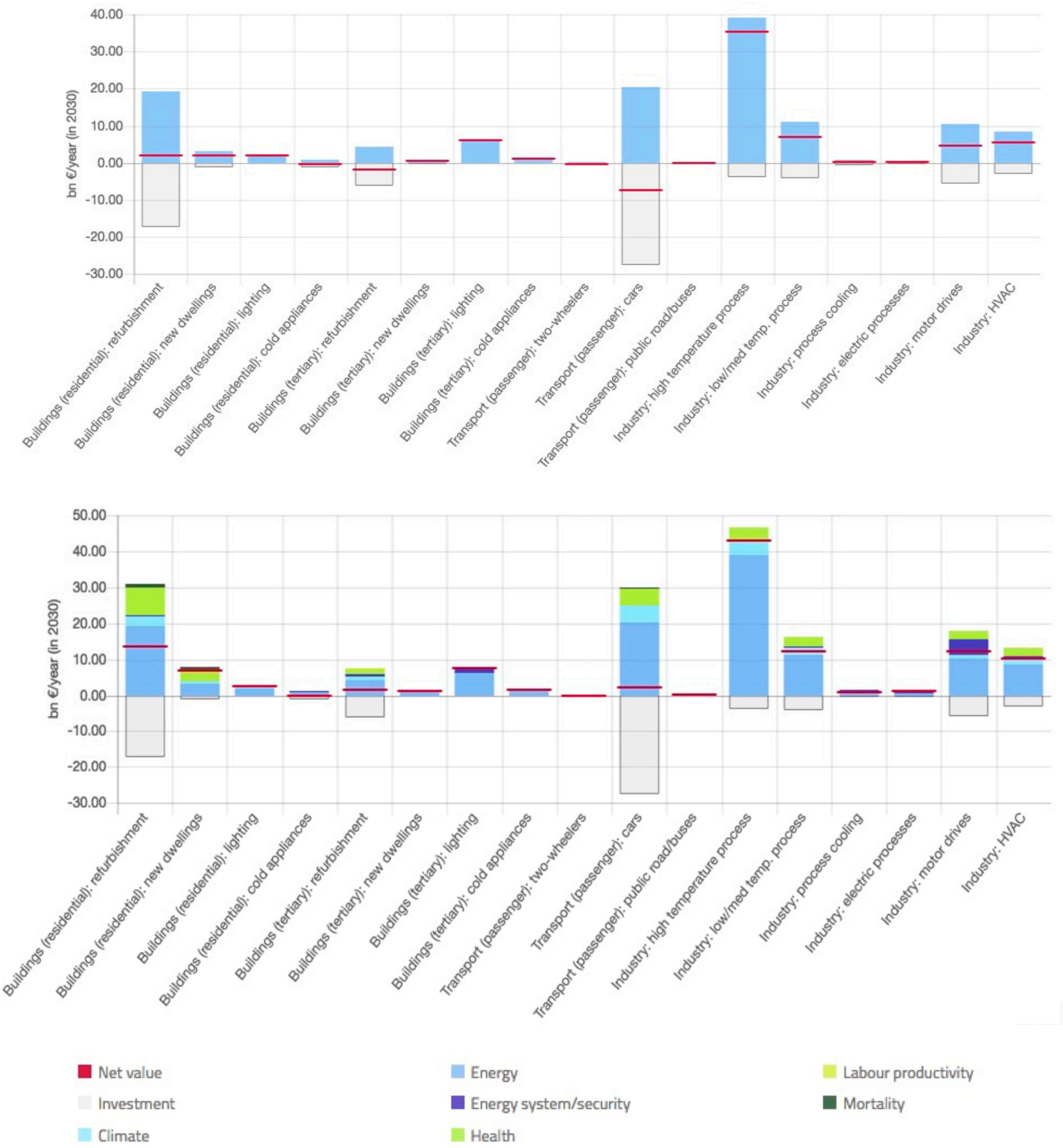

Figure 2. Cost-benefit analysis of EEI actions across EU28 (bn€ per year in 2030). Upper graph: excluding and lower graph: including MI (excluding modal shift and trucks).

4. Discussion

Figure 3 summarises the overall COMBI results. If including only those monetized impacts to a CBA where impact pathway mapping yielded that no overlaps exist, the analysis finds that annually

- For all COMBI actions (excl. modal shift and trucks), MI amount to 61 bn€ plus 131 bn€ of energy cost savings, i.e., MI add approx. 50% of energy cost savings to the benefits
- For the residential building refurbishment example, MI amount 13.6 bn€ plus 19.2 bn€ of energy cost savings, i.e., MI add approx. 70% of energy cost savings to the benefits

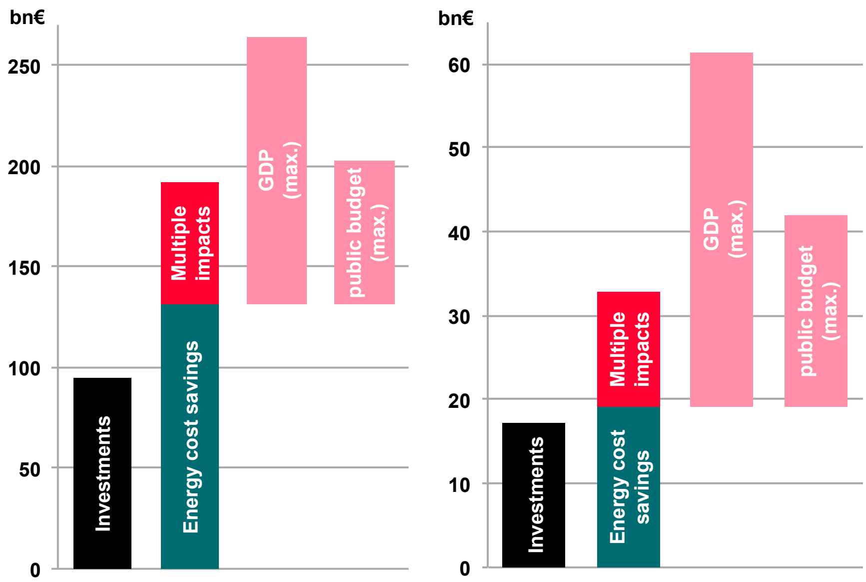

Figure 3. Investments, energy cost savings and multiple impacts (bn€ annual in 2030).

Macro-economic impacts (aggregate demand/GDP and public budget) are not included in the CBA due to partial overlaps that could not be quantified and due to uncertain valuability (impacts will only become effective, if the national economy has idle resources). However, those are the potentially highest impacts. The figures demonstrate that

- For all actions (excl. modal shift and trucks), GDP may add value up to additional 100% of energy cost savings, and public budget another 50% (which however may partially overlap with GDP increases)
- For residential buildings, this relation is even higher, namely 220% of energy cost savings for the GDP effect and 120% for the public budget effect

The conservative CBA approach as presented here finds that the inclusion of MI quantifications to EE impact assessments would increase the benefit side by at least 50–70%. Yet these calculations exclude numerous impacts which were either not possible to be quantified or monetized, or for which a double-counting potential was found. Including economic impacts of GDP and/or public budget may double or triple the size of MI–but because of their double-counting potential and uncertain realisation they have not been included in the CBA as presented here. In any case, cost-effectiveness of EEI actions improves substantially from a societal perspective when including MIs.

As any forward-looking research that involves modelling, the various models applied for multiple impact estimation for this research have to draw on numerous assumptions and external data projections all of which are subject to uncertainty. Researchers intended to provide maximum transparency on the caveats (for a summary, see [46]) and uncertainties. However, as all modelling results, estimations are not projections but estimates, based on best available methods. A number of issues need to be highlighted:

The input data for these impact estimations is based on the assumption that additional EEI actions (beyond a current policy scenario) are implemented. Additional ambitious and dedicated policy measures are a precondition for the implementation of these actions. Such policies were not subject of this work. At the same time, we implemented an ambitious reference scenario with full compliance with current policies.

Some impacts will only materialise if targeted policies are implemented, such as targeted energy poverty policies that drive building renovations primarily for the vulnerable population (e.g., through addressing the social housing sector, split incentives dilemma or financing issues).

Some impacts will only materialise if certain framework conditions are met, e.g., short-term macro-economic effects only will be realised in a situation of free economic capacities that can absorb the additional demand stimulus and turn this into additional turnover and employment. As the projection of business cycles until 2030 is not possible, effects can be estimated only conditional on free capacities.

All impact indicators vary between countries and EEI actions. This reflects different country contexts represented as detailed as possible in the models. Still, in order to provide a better national foundation of dedicated policies, additional country-specific research is needed. Results from this research indicate at a first step which impacts are of high importance and how they vary within the EU.

Multiple impacts may show large effects in physical units, but monetised values seem small for certain impacts and countries. This points to contested monetization methodologies (e.g., low "values of life years" in lower-income countries) and ethical debates around the valuation of human health and lives [49]. This scientific and ethical debate is not concluded and may lead to different evaluations at national levels if following diverging approaches.

Other caveats and open issues may be classified to three categories: (1) missing data and data limitations, (2) model limitations and (3) linking models and modelling interdependencies. These categories also indicate needs for future research. The presented research is the first step to integrate multiple impacts of energy efficiency into cost-benefit analyses. Future research efforts can build on these results and improve them by addressing the caveats and open issues.

5. Conclusions

The total greenhouse gas emission reduction potential of the COMBI energy efficiency actions amounts to 362 Gt CO_{2eq}/y. Our research found that multiple impacts of implementing these actions are substantial: especially health impacts from reduced air pollution avoid e.g., only for PM2.5 reductions, yearly losses of more than 10,000 disability-adjusted life years (DALY) and 230,000 years of life lost (YOLL) can be avoided every year. The total EU material footprint can be reduced by over 850 Mt/y of material resources. The improvement of building conditions can alleviate poverty, if policies are directed towards the vulnerable population, up to 24,000 premature deaths and 22,300 DALYs could be avoided annually. Economic impacts are substantial, also: up to 1% increase in GDP and 2.3 mn job-years could be stimulated, energy prices may decrease 1–3% below the reference scenario.

When monetised, these multiple impacts amount to around 50–70% of energy cost savings. This estimation still excludes many impacts because of potential double-counting. Especially, economic impacts as the largest impacts are excluded, but might increase the benefit side substantially, if double-counting could be ruled out in further research.

The inclusion of multiple impacts substantially alters cost-benefit analyses of energy efficiency. An omission of MI in cost-benefit analyses reduces the cost-effectiveness of EEI actions below their actual value and leads to an underinvestment (sub-optimal level) in EE from a societal perspective. The same is true if not all impacts are included or are underestimated. If MI are included into the assessment of policy scenarios, higher ambitions on EE targets are more cost-effective.

A more complete picture of the positive and negative impacts of EE is a precondition for a more complete assessment of policy impacts on a number of policy targets. Reliable quantifications of impacts will support policy makers in taking informed decisions, e.g., in prioritising EE vs. expanding sustainable energy supply, but also with respect to policy design and implementation and in selecting instruments and targets that maximize social welfare.

Quantified values of MI are already used in policy-making (e.g., as arguments in impact assessments for policy options) to gain support for the implementation of EE policies and to increase the attractiveness of investments in EE. However, impacts are captured only selectively and play only a secondary role. Making more explicit the MI that concern policy targets of non-energy departments (e.g., health, social welfare, economy) may lead to a convergence of interest and may encourage inter-departmental and cross-sectoral cooperation in policy making to pursue common goals in the future.

Author Contributions: Overall project and funding coordination, organisation and coordination of data templates and gateways, review and quality assurance of all reporting, website and online-tool programming oversight, cost-benefit calculations, policy investigation, writing-draft preparation, review and editing, J.T. (Johannes Thema); overall project and funding coordination, review and quality assurance of all reporting, cost-benefit calculations, policy investigation, writing-draft preparation, review and editing, F.S.; conceptualisation of input data and scenarios, conceptualisation and writing of impact quantification on energy security impacts, J.C.; conceptualisation and writing of air quality impacts, air quality-related and energy poverty-related health impacts, N.M.; conceptualisation and writing of impact on productivity and impact synthesis sections, S.C.; conceptualisation and writing of sections on resource quantification, J.T. (Jens Teubler); methodology supervision and data validation, S.T.; conceptualisation and writing of impact on productivity and impact synthesis sections, D.Ü.-V.; conceptualisation and writing of economic impacts, M.B.H.; conceptualisation, methodology, supervision, writing-review and editing, project administration for the work on energy poverty-related impacts, S.B.; policy investigation and writing-original draft preparation, J.R.; review of economic impacts, S.W.

Funding: This research was funded by European Union's Horizon 2020 research and innovation programme under grant agreement No 649724. The content of this contribution reflects only the author's views. The Agency is not responsible for any information it contains.

Acknowledgments: We thank especially the two external reviewers on behalf of EASME/EU-Commission who provided detailed feedback to project methodologies and the online tool that helped us clarify important methodological issues and improve accessibility substantially. We are also indebted to the great support of staff at IIASA who made possible the quantification of air pollution impacts and related health and ecosystem impacts by running the GAINS model on COMBI data.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Overview of COMBI impact indicators and respective quantification methodologies.

#	Impact Indicators	Quantification Methodology
Air pollution [19]	Human health	Reduction in premature mortality due to the exposure of different outdoor pollutants by using GAINS model
	Eco-systems: acidification	Total ecosystem area spared from acidification by using GAINS model
	Eco-systems: eutrophication	Total ecosystem area spared from eutrophication by using GAINS model
	Air pollution: Emissions (impact mid-points)	Reduction in outdoor air pollutants emission from fuel combustion and transportation by using GAINS model
Resources [20]	Material Footprint (total of fossil fuels, (biotic) minerals, metal ores, unused extraction)	Sum of extracted abiotic (fossil fuels, metal ores, minerals) and biotic raw materials from nature, including the extraction of economic unused materials. Model: Material Flow Accounting (MFA).
	Fossil fuels	MFA of all fossil fuel raw materials from nature that are put to an economic use.
	Minerals	MFA of all raw mineral materials from nature that are put to an economic use.
	Metal ores	MFA of all metal ores raw materials from nature that are put to an economic use.
	Biotic raw materials	MFA of all biotic raw materials from nature that are put to an economic use.
	Unused extraction	MFA of materials that are extracted from nature and are not translocated from site or put to a direct economic use. Includes overburden, by-catch and waste on site.
	Direct carbon emissions	Direct carbon emissions based on emission factors for fuel types from the IPCC reports. Values in CO_2 equivalents/unit of energy.
	Carbon Footprint (GWP, life-cycle missions incl. direct emissions)	Life-cycle Assessment of characterised GHG and their global warming potential (GWP) in 100 years (GWP 100a). Characterisation factors are based on the IPCC reports.

Table A1. *Cont.*

#	Impact Indicators	Quantification Methodology
Social welfare [21] (energy poverty) [22]	Excess winter mortality attributable to inadequate housing (thermal comfort)	Reduction in premature mortality due to inadequate heating, COMBI model.
	Asthma burden of disease attributable to inadequate housing (indoor humidity)	Reduction in asthma burden of disease due to dampness in the building, COMBI model.
	Active days (impact through health-asthma, allergy, cardiovascular disease, cold and flu, traffic time saved)	Dose-response model to calculate the indoor exposure-related active days and basic reduction method is used to calculate congestion-related active days, COMBI model.
	Workforce performance	Basic performance improvement equation is used to calculate workforce performance, COMBI model.
Macro-Economic impacts [23]	Temp. (business-cycle) aggregate demand (potential GDP increase)	Input/output analysis and fiscal multiplier analysis based on additional investment and energy (cost) savings
	Temp. (business-cycle) employment	Input/output analysis and fiscal multiplier analysis
	Temp. (business-cycle) public budget effects	Input/output analysis, fiscal multiplier analysis and budgetary semi-elasticities
	Fossil fuel price effects	General equilibrium modelling (Copenhagen Economics Global Climate and Energy Model-CECEM)
	Changes to marginal abatement costs	General equilibrium modelling (CECEM)
	Terms of Trade effect	General equilibrium modelling (CECEM)
	Sectoral shifts	General equilibrium modelling (CECEM)
Energy security [24]	Energy intensity	Final energy demand reduced by COMBI actions divided by GDP
	Import dependency	COMBI Energy balance model. Change in net imports. Net imports of fuels multiplied by their respective energy prices.
	Aggregated energy security	COMBI Energy balance model. Relevant output is net imports. Allocation model to determine country of origin of imports. Use of risk indicators to assess political risks.
	Avoided electric power generation & investment costs	COMBI Energy balance model. Power sector model to determine mix of power plant and cogeneration plant technologies and capacities. Relevant generation output is net power output. Avoided investment costs: avoided power capacity multiplied by specific capital costs per technology.
	Derated reserve capacity rate	COMBI Energy balance model and power sector model. Model to determine peak loads and reserve capacities based on annual load duration curves.

Source: [46].

References

1. European Commission Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC 2012. Available online: eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0027&from=DE (accessed on 19 July 2019).
2. Ürge-Vorsatz, D.; Novikova, A.; Sharmina, M. Counting good: Quantifying the co-benefits of improved efficiency in buildings. In Proceedings of the European Council for an Energy Efficient Economy, Hyères, France, 1–6 June 2009.
3. DG Environment TREMOVE: An EU-wide Transport Model. Available online: Ec.europa.eu/environment/archives/air/models/tremove.htm (accessed on 11 July 2019).
4. Büker, P.; Morrissey, T.; Briolat, A.; Falk, R.; Simpson, D.; Tuovinen, J.P.; Alonso, R.; Barth, S.; Baumgarten, M.; Grulke, N.; et al. DO3SE modelling of soil moisture to determine ozone flux to forest trees. *Atmos. Chem. Phys.* **2012**, *12*, 5537–5562. [CrossRef]

5. Amann, M. EC4MACS Modelling Methodology: The GAINS Integrated Assessment Model. Laxenburg, Austria: European Consortium for Modelling of Air Pollution and Climate Strategies EC4MACS. Available online: Ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=EC4MACS_GAINS_Methodologies_Final.pdf (accessed on 11 July 2019).
6. Holland, M. *European Commission ExternE-External Costs of Energy*; European Commission: Brussels, Belgium, 1995.
7. Mzavanadze, N. *Literature Review on Avoided Air Pollution Impacts of Energy Efficiency Measures*; COMBI: Manchester, UK, 2015.
8. European Commission. *Report on Critical Raw Materials for the EU: Report of the Ad hoc Working Group on Defining Critical Raw Materials*; European Commission: Brussels, Belgium, 2014.
9. BMU. *German Resource Efficiency Programme (ProgRess): Programme for the Sustainable Use and Conservation of Natural Resources*; Federal Ministry for the Environment, Nature Conservation and Nuclear Safety: Berlin, Germany, 2015.
10. Teubler, J.; Bienge, K.; Wiesen, K. *Literature Review on Resource Benefits*; COMBI: Wuppertal, Germany, 2015.
11. Stewart, M.; Weidema, B.P. A Consistent Framework for Assessing the Impacts from Resource Use-A focus on resource functionality. *Int. J. Life Cycle Assess.* **2005**, *10*, 240–247. [CrossRef]
12. Finkbeiner, M.; Inaba, A.; Tan, R.; Christiansen, K.; Klüppel, H.J. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *Int. J. Life Cycle Assess.* **2006**, *11*, 80–85. [CrossRef]
13. Hiederer, R. *Institute for Environment and Sustainability. International Reference Life Cycle Data System (ILCD) Handbook: General Guide for Life Cycle Assessment: Provisions and Action Steps*; Publication Office of the European Union: Brussels, Belgium, 2011.
14. Hinterberger, F.; Giljum, S.; Hammer, M. *Material Flow Accounting and Analysis (MFA): A Valuable Tool for Analyses of Society-Nature Interrelationships*; Background Paper; SERI: Vienna, Austria, 2003.
15. *European Commission Economy-Wide Material Flow Accounts and Derived Indicators: A Methodological Guide*; Publication Office of the European Union: Brussels, Belgium, 2001.
16. Weisz, H.; Krausmann, F.; Eisenmenger, N.; Schütz, H.; Haas, W.; Schaffartzik, A. *Economy-wide material flow accounting. A compilation guide*; Eurostat and the European Commission: Brussels, Belgium, 2007.
17. Clinch, J.P.; Healy, J.D. Housing standards and excess winter mortality. *J. Epidemiol. Community Health* **2000**, *54*, 719–720. [CrossRef] [PubMed]
18. Brophy, V.; Clinch, J.P.; Convery, F.J.; Healy, J.D.; King, C.; Lewis, J.O. *Homes for the 21st Century: The Costs and Benefits of Comfortable Housing*; Energy Action Limited: Dublin, Ireland, 1999.
19. Clinch, J.P.; Healy, J.D. Cost-benefit analysis of domestic energy efficiency. *Energy Policy* **2001**, *29*, 113–124. [CrossRef]
20. Clinch, J.P.; Healy, J.D. Valuing improvements in comfort from domestic energy-efficiency retrofits using a trade-off simulation model. *Energy Econ.* **2003**, *25*, 565–583. [CrossRef]
21. Herrero, S.T.; Ürge-Vorsatz, D.; Petrichenko, K. Fuel poverty alleviation as a co-benefit of climate investments: Evidence from Hungary. In Proceedings of the European Council for an Energy Efficient Economy Summer Study (ECEEE), Hyères, France, 8 June 2013; pp. 1605–1616.
22. Mzavanadze, N.; Kelemen, A.; Ürge-Vorsatz, D. *Literature Review on Social Welfare Impacts of Energy Efficiency Improvement Actions*; COMBI: Manchester, UK, 2015.
23. Pearson, D.; Skumatz, L.A. Non-Energy Benefits Including Productivity, Liability, Tenant Satisfaction, and Others—What Participant Surveys Tell Us about Designing and Marketing Commercial Programs. In Proceedings of the 2002 Summer Study on Energy Efficiency in Buildings, Citeseer, Hyères, France, 16 December 2002.
24. Seppanen, O.; Fisk, W.J.; Faulkner, D. Control of temperature for health and productivity inoffices. *ASHRAE Trans.* **2004**, *111*, 55448.
25. Worrell, E.; Laitner, J.A.; Ruth, M.; Finman, H. Productivity benefits of industrial energy efficiency measures. *Energy* **2003**, *28*, 1081–1098. [CrossRef]
26. European Commission Commission staff working document impact assessment. Accompanying the document Proposal for a Directive of the European Parliament and of the Council amending Directive 2012/27/EU on Energy Efficiency. SWD/2016/0405 final-2016/0376 (COD) 2016. Available online: eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52016SC0405 (accessed on 19 June 2019).

27. *European Commission The Macro-Level and Sectoral Impacts of Energy Efficiency Policies*; European Commission: Brussels, Belgium, 2017.
28. Ra, T. *The Economics of Input-Output Analysis*; Cambridge University Press: Cambridge, UK, 2005.
29. Mourre, G.; Astarita, C.; Princen, S. *Adjusting the Budget Balance for the Business Cycle: The EU Methodology*; Directorate General Economic and Financial Affairs (DG ECFIN) European: Brussels, Belgium, 2014.
30. Grigoli, F.; Herman, A.; Swiston, A.; Di Bella, G. Output gap uncertainty and real-time monetary policy. *Rus. J. Econ.* **2015**, *1*, 329–358. [CrossRef]
31. Naess-Schmidt, S.; Westh-Hansen, M.B.; Von Below, D. *Literature Review on Macroeconomic Effects of Energy Efficiency Improvement Actions*; COMBI: Copenhagen, Denmark, 2015.
32. Spooner, M.; Tomasi, M.; Arnoldus, P.; Johannesson-Linden, Ǻ.; Kalantzis, F.; Maincent, E.; Pienkowski, J.; Rezessy, A. *Member States' Energy Dependence: An Indicator-Based Assessment*; European Economy: Brussels, Belgium, 2013.
33. Böhringer, C.; Keller, A. Energy Security: AnImpact Assessment of the EU Climate and Energy Package. In *Wirtschaftswissenschaftliche Diskussionspapiere*; University of Oldenburg: Oldenburg, Germany, 2011.
34. Argonne National Laboratory Energy Systems-ENPEP-BALANCE: A Tool for Long-term Nuclear Power Market Simulations. Available online: Ceeesa.es.anl.gov/projects/enpep_balance.html (accessed on 12 July 2019).
35. Quintel Intelligence Energy Transition Model. Available online: Quintel.com/etm (accessed on 12 July 2019).
36. Enerdata. Costs and Benefits to EU Member States of 2030 Climate and Energy Targets. Publishing service UK; 2014. Available online: assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/285505/costs_benefits_eu_states_2030_climate_and_energy_targets_enerdata_report.pdf (accessed on 19 July 2019).
37. Lund, H.; Mathiesen, B.V. Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050. *Energy* **2009**, *34*, 524–531. [CrossRef]
38. Heaps, C. *Long-Range Energy Alternatives Planning (LEAP) System*; Stockholm Environmental Institute: Stockholm, Sweden, 2015.
39. Couder, J. *Literature Review on Energy Efficiency and Energy Security, Including Power Reliability and Avoided Capacity Costs*; COMBI: Antwerp, Belgium, 2015.
40. Copenhagen Economics. *Multiple Benefits of Investing in Energy Efficient Renovation of Buildings: Impact on Public Finances*; Renovate Europe: Copenhagen, Denmark, 2012.
41. Campbell, N.; Ryan, L.; Rozite, V.; Lees, E.; Heffner, G. *Capturing the Multiple Benefits of Energy Efficiency*; IEA: Paris, France, 2014.
42. Naess-Schmidt, S.; Westh-Hansen, M.B. *Multiple Benefits of Energy Renovations of the Swedish Building Stock*; Swedish Energy Agency and the National Board of Housing, Building and Planning: Copenhagen, Denmark, 2016.
43. Suerkemper, F.; Thema, J.; Thomas, S.; Dittus, F.; Kumpaengseth, M.; Beerepoot, M. Benefits of energy efficiency policies in Thailand: An ex-ante evaluation of the energy efficiency action plan. *Energy Effic.* **2016**, *9*, 187–210. [CrossRef]
44. European Commission Proposal for a Directive of the European Parliament and of the Council amending Directive 2012/27/EU on energy efficiency 2016. Available online: eur-lex.europa.eu/legal-content/EN/TXT/?qid=1485938766830&uri=CELEX:52016PC0761 (accessed on 19 June 2019).
45. Ürge-Vorsatz, D.; Kelemen, A.; Tirado-Herrero, S.; Thomas, S.; Thema, J.; Mzavanadze, N.; Hauptstock, D.; Suerkemper, F.; Teubler, J.; Gupta, M. Measuring multiple impacts of low-carbon energy options in a green economy context. *Appl. Energy* **2016**, *179*, 1409–1426. [CrossRef]
46. Thema, J.; Rasch, J. *Quantification Report (Summary of Quantifications, Methodologies and Introduction to Results)*; COMBI: Wuppertal, Germany, 2018.
47. Couder, J. *Description of End-Use Energy Efficiency Improvement Actions in the Residential, Tertiary, Transport and Industry Sectors*; COMBI: Antwerp, Belgium, 2018.
48. Couder, J. *Overview of COMBI Scenarios and How They Were Constructed (Annex)*; COMBI: Antwerp, Belgium, 2018.
49. Mzavanadze, N. *Quantifying Air Pollution Impacts of Energy Efficiency. D3.4*; COMBI: Manchester, UK, 2018.
50. Mzavanadze, N. *Quantifying Energy Poverty-Related Health Impacts of Energy Efficiency. D5.4*; COMBI: Manchester, UK, 2018.

51. Teubler, J.; Bienge, K.; Kiefer, S. *Methodology and Quantification of Resource Impacts from Energy Efficiency in Europe. D4.4*; COMBI: Wuppertal, Germany, 2018.
52. Chatterjee, S.; Ürge-Vorsatz, D. *Quantification of Productivity Impacts. D5.4a*; COMBI: Budapest, Hungary, 2018.
53. Naess-Schmidt, S.; Westh-Hansen, M.B.; Wilke, S.; Modvig Lumby, B. *Macro-Economic Impacts of Energy Efficiency. D6.4*; COMBI: Copenhagen, Denmark, 2018.
54. Couder, J. *Quantification and Monetization of Selected Energy System and Security Impacts. D7.4*; COMBI: Antwerp, Belgium, 2018.
55. Chatterjee, S.; Ürge-Vorsatz, D.; Thema, J.; Kelemen, A. *Synthesis Methodology. D2.4*; COMBI: Budapest, Hungary, 2018.
56. IIASA GAINS Online. Greenhouse Gas-Air Pollution Interactions and Synergies. Available online: Gains.iiasa.ac.at/models/index.html (accessed on 8 July 2019).
57. Amann, M.; Bertok, I.; Borken-Kleefeld, J.; Cofala, J.; Heyes, C.; Höglund-Isaksson, L.; Klimont, Z.; Nguyen, B.; Posch, M.; Rafaj, P.; et al. Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. *Environ. Model. Softw.* **2011**, *26*, 1489–1501. [CrossRef]
58. Schmidt-Bleek, F.; Bringezu, S.; Hinterberger, F.; Liedtke, C.; Spangenberg, J.H.; Stiller, H.; Welfens, M.J. *MAIA: Einführung in Die Material-Intensitäts-Analyse Nach Dem MIPS-Konzept*; Birkhäuser: Berlin, Germany, 1998.
59. Liedtke, C.; Bienge, K.; Wiesen, K.; Teubler, J.; Greiff, K.; Lettenmeier, M.; Rohn, H. Resource Use in the Production and Consumption System—The MIPS Approach. *Resources* **2014**, *3*, 544–574. [CrossRef]
60. Saurat, M.; Ritthoff, M. Calculating MIPS 2.0. *Resources* **2013**, *2*, 581–607. [CrossRef]
61. Schmidt-Bleek, F. *Das MIPS-Konzept: Weniger Naturverbrauch, Mehr Lebensqualität Durch Faktor Zehn*; Droemer Knaur: München, Germany, 2000.
62. Teubler, J.; Kiefer, S.; Liedtke, C. Metals for Fuels? The Raw Material Shift by Energy-Efficient Transport Systems in Europe. *Resources* **2018**, *7*, 49. [CrossRef]
63. Bernstein, L.; Bosch, P.; Canziani, O.; Chen, Z.; Christ, R.; Davidson, O.; Hare, W.; Huq, S.; Karoly, D.; Kattsov, V. *Climate Change 2007: Synthesis Report: An. Assessment of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2008.
64. Vogtländer, J.G. *The Model of the Eco-Costs/Value Ratio: A new LCA Based Decision Support Tool*; TU Delft: Delft, Netherlands, 2002; Available online: https://repository.tudelft.nl/islandora/object/uuid:a97d2ec9-4bf8-44f4-98b2-f4d83a7b5399/datastream/OBJ/download (accessed on 19 July 2019).
65. Wiesen, K.; Wirges, M. From cumulated energy demand to cumulated raw material demand: The material footprint as a sum parameter in life cycle assessment. *Energy Sustain. Soc.* **2017**, *7*, 13. [CrossRef]
66. IHME Measuring What Matters. Available online: Healthdata.org (accessed on 10 July 2019).
67. Murray, C.J.L.; Lopez, A.D. Measuring global health: Motivation and evolution of the Global Burden of Disease Study. *Lancet* **2017**, *390*, 1460–1464. [CrossRef]
68. Bouzarovski, S.; Petrova, S. A global perspective on domestic energy deprivation: Overcoming the energy poverty–fuel poverty binary. *Energy Res. Soc. Sci.* **2015**, *10*, 31–40. [CrossRef]
69. Gracceva, F.; Zeniewski, P. A systemic approach to assessing energy security in a low-carbon EU energy system. *Appl. Energy* **2014**, *123*, 335–348. [CrossRef]
70. Greenleaf, J.; Harmsen, R.; Angelini, T.; Green, D.; Williams, A.; Rix, O.; Lefevre, N.; Blyth, W. Analysis of impacts of climate change policies on energy security. In *Being Final Report of Ecofys, ERAS and RedPoint Energy by Order of: European Commission DG Environment*; European Commission: Brussels, Belgium, 2009.
71. Ürge-Vorsatz, D.; Herrero, S.T.; Dubash, N.K.; Lecocq, F. Measuring the Co-Benefits of Climate Change Mitigation. *Annu. Rev. Environ. Resour.* **2014**, *39*, 549–582. [CrossRef]
72. Wuppertal Institut; University of Antwerp; University of Manchester; Copenhagen Economics; Advanced Buildings and Urban Design COMBI Online Tool. Available online: Combi-project.eu/tool/ (accessed on 10 July 2019).
73. Thema, J. *Online Tool Manual & Documentation (Incl. Technical Details & CBA Formulae)*; COMBI: Wuppertal, Germany, 2018.