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A Comparative Analysis of Annual Market Investments in Energy Supply and End-useTechnologies

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Abstract

Whereas the need to mobilize investment in energy supply technologies is broadly understood, with the current level of investment estimated in the order of $0.7 – 0.9 trillion a year, there is a notable absence of analogous investment data for end-use technologies. This paper presents a global, bottom-up estimate of total investments in end-use energy technologies based on volume data and cost estimates for 2005. Total investment in end-use technologies was conservatively found to be in the order of $0.3 - 4 trillion depending on the definition of end-use technology used.

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A Comparative Analysis of Annual Market Investments in Energy Supply and End-use Technologies

Charlie Wilson & Arnulf Grubler

1. Introduction: Investment Needs for Energy System Transformation

Across a wide range of future scenarios, reducing energy intensity by improving the efficiency of end-use technologies is a lower cost complement to reducing the carbon intensity of the energy supply in the nearer term (Ürge-Vorsatz and Metz 2009). Modeling assessments find energy efficiency improvements in buildings, appliances, vehicles, industrial processes, and so on, to represent the largest, and least costly source of potential emission reductions (p40, IEA 2008). The ranking of efficiency and conservation as the most important mitigation options is also robust to different scenario and technology assumptions (Riahi, Grubler et al. 2007). Supply curves of emission reductions similarly highlight the low or negative marginal abatement costs associated with end-use technologies (Enkvist, Naucler et al. 2007).

Substantive investments are required to ensure both efficient end-use technologies and low carbon energy supply technologies[1] diffuse widely throughout the energy system (Nakicenovic and Rogner 1996). Financial resources to support research to bring innovations to market are an integral part of this challenge. Trends in, and uses of, these 'innovation investments' are addressed elsewhere (Nemet and Kammen 2007; Gallagher, Anadon et al. 2011). The empirical focus of this paper is on 'diffusion' investments in market settings: building power plants and refineries; manufacturing cars and solar panels; installing heating systems and light bulbs.

The magnitude of current and future 'diffusion' investments in energy supply technologies is relatively well characterized in both reference (or baseline) scenarios and in climate change mitigation scenarios (IEA 2009). Analogous estimates for end-use technologies are comparatively weak and patchy. This prevents like-for-like comparisons of capital investment requirements between the supply and demand sides of the energy system.

In this paper, we briefly review current estimates of global diffusion investments in energy technologies, and distinguish the different approaches used. We then provide bottom-up, granular estimates of current investments in the principal types of end-use technology worldwide. (By granular, we mean disaggregated to, or resolved at, the level of individual technologies). We compare the magnitude and diversity of these end-use

[1] *Energy supply technologies* extract, process, transport and convert primary energy into energy carriers, and distribute them to the point of use (e.g., oil wells, drilling rigs, pipelines, refineries, tankers, gas stations); *energy end-use technologies* provide useful energy services to final users (e.g., mobility in the transportation sector, space conditioning in the residential and commercial sectors).

investments to analogous estimates for the energy supply. We conclude by arguing for the centrality of end-use technology investments in the analysis of global energy system challenges, particularly climate change mitigation.

2. Energy Technology Investment Estimates

2.1. Current Investments in Energy Technologies

Current levels of investment in the global energy system are estimated by the International Energy Agency (IEA) in the range \$0.7 – 0.9 trillion a year (IEA 2008; IEA 2009). This is in line with an estimate for the Global Energy Assessment of \$0.96 trillion (Riahi, Dentener et al. 2011). Both calculate energy supply investments only, with over half the total attributed to electricity plant and transmission infrastructure. (All investment data in this paper are expressed in 2005\$ using global GDP deflators, unless otherwise noted). These data broadly compare with earlier estimates of \$0.6 trillion a year in the IEA's World Energy Investment study (IEA 2003), and annual averages of \$0.7 - 1.1 trillion and \$1 trillion for the period 1990 - 2020 taken from, respectively, the Global Energy Perspectives study (Nakicenovic and Rogner 1996) and the World Energy Council study (WEC 1993).

2.2. Climate Change Mitigation & Future Investments in Energy Technologies

Estimating future energy technology investment needs is one approach to costing climate change mitigation. Estimates are either expressed in absolute terms as total investments, or in relative terms as incremental investments needed to move from some reference or baseline scenario to a defined mitigation scenario.

Alternative approaches are to express incremental mitigation costs relative to a reference scenario in terms of economy-wide impacts on GDP (e.g., Stern 2006; Edenhofer, Knopf et al. 2010) or in terms of sectoral or economy-wide abatement costs (Levine, Ürge-Vorsatz et al. 2007; van Vuuren, Hoogwijk et al. 2009). Ranking technologies by their abatement cost per tCO_2 (y-axis) in combination with their emission reduction potential (x-axis) also generates supply curves for emission reductions (McKinsey 2009) which are widely used in modelling studies (Cofala, Purohit et al. 2008). Here, however, our interest is in the investment estimates generated by such studies.

The most widely cited investment figures are published by the International Energy Agency in their authoritative annual report, the World Energy Outlook. This details the dominant challenges for the global energy system and projects its development over a decadal timeframe (IEA 2009). The 'Reference Scenario' of the 2009 World Energy Outlook identifies cumulative investment costs in the period to 2030 equivalent to around \$1 trillion a year (p104, IEA 2009). This total investment estimate disaggregates into power generation and transmission (53%), upstream oil and gas (23% and 20%), and coal (3%): all energy supply technologies. Total investment requirements are not estimated for end-use technologies.

Incremental investments required in end-use technologies to mitigate climate change are estimated. Relative to the costs of the ‘Reference Scenario’ over the period to 2030, the additional costs of a ‘450 Scenario’ are estimated at $0.4 trillion per year (p258, IEA 2009). The ‘450 Scenario’ describes a stabilization of atmospheric concentrations of CO_2-equivalents at 450 ppmv. Around 80% of the additional investment in the 450 Scenario is in end-use technologies, disaggregated into transport (44%), buildings (24%) and industry (10.5%), with the remainder attributed to energy supply technologies (p104, IEA 2009). Total investments in end-use technologies in the mitigation scenario can not be estimated as the total investments in the reference scenario is not known.

Table 1 summarizes these and other capital investment estimates illustrating the asymmetric treatment of energy supply and end-use technologies. Total investments costs are only estimated for energy supply technologies. The corresponding column for end-use technologies in Table 1 is blank except for the IEA (2008) study which is discussed below. To the extent they are estimated, investment costs in end-use technologies are expressed in incremental terms (i.e., relative to a reference scenario).

The Global Energy Assessment scenarios, for example, report cumulative investment costs to 2050 which combine total investments in energy supply technologies and incremental investments in end-use efficiency to meet a 2^oC stabilization target (Riahi, Dentener et al. 2011). Total investments in end-use technologies are not reported.

Another recent study used three modeling groups’ estimates of the investment requirements to reach a 450ppm CO_2-only stabilization target (Luderer, Bosetti et al. 2009). In this case, total investment requirements were estimated for both reference and mitigation scenarios, but only for 5 categories of energy supply technology.

An earlier study based on detailed modeling representations of the residential, commercial, industrial and transportation end-use sectors did report the incremental investment costs for end-use technologies in a 2^oC climate stabilization scenario (Hanson and Laitner 2006). In this case, however, total investments in the reference scenario were not reported.

The lack of total investment estimates for end-use technologies in both reference and mitigation scenarios prevents a meaningful, holistic appreciation of the financing needs of future energy system transformation. Estimating incremental but not total investments creates an additional problem as the magnitude of incremental investments in the mitigation scenario depends on the extent to which total investments are already assumed to characterize the reference scenario (van Vuuren, Hoogwijk et al. 2009). This problem is particularly marked for end-use technologies in reference scenarios with strongly falling energy intensity, giving rise to a substantive reduction in apparent end-use investment requirements relative to energy supply investments (Riahi, Grubler et al. 2007).

Table 1. Comparison of Future Energy Supply and End-Use Technology Investment Needs Globally (Annual Approximations).

STUDY	REPORTED INVESTMENT DATA (AS BASIS FOR ANNUAL ESTIMATES)	*TOTAL* ANNUAL INVESTMENT NEEDS (APPROXIMATED, 2005$)		*INCREMENTAL* ANNUAL INVESTMENT NEEDS (APPROXIMATED, 2005$)			ASSOCIATED INTEGRATED ASSESSMENT MODELS[A]
		SUPPLY	END-USE	SUPPLY	END-USE	BASIS OF INCREMENTAL ESTIMATES	
(Nakicenovic and Rogner 1996)	cumulative investment to 2020 (1990$) in three scenarios	$0.7 - 1.1 tr	-	-	-	no reference scenario reported	MESSAGE
(Hanson and Laitner 2006)	average annual investment to 2060 (2000$)	-	-	-$0.01 tr[b]	$0.07 tr	from reference to mitigation scenario (2°C stabilisation)	AMIGA
(IEA 2008)	cumulative investment to 2050 (2005$)	$0.6 tr	$5.0 tr[c]	$0.1 tr	$0.9 tr	from reference to 'BLUE scenario' (50% reduction in CO_2 emissions by 2050)	IEA models
(IEA 2009)	cumulative investment to 2030 (2008$)	$1.0 tr	-	$0.1 tr	$0.4 tr	from reference to '450 Scenario' (450 ppmv CO2-eq.)	IEA models
(Luderer, Bosetti et al. 2009)	average annual investment to 2030 (2005$)	$0.5 - 0.6 tr	-	-$0.2 tr[b] - $0.7 tr	-	from reference to mitigation scenario (450 ppmv CO_2 only)	IMACLIM, REMIND, WITCH
(Riahi, Dentener et al. 2011)	cumulative investment to 2050 (2005$) in three scenarios	$1.4 - 1.8 tr	-	-	$0.3 - 0.5 tr	no reference scenario reported	MESSAGE
(van Vuuren, Hoogwijk et al. 2009)	$0.1 - 1.0 tr abatement costs in 2030 (2000$)	not commensurate with investment data; not disaggregated by energy supply and end-use				from reference to mitigation scenario (450 ppmv CO_2-eq.)	AIM, E3MG, ENV-Linkages, IMAGE, MESSAGE, WorldScan
(Stern 2006)	-2% to 5% loss of GDP	not commensurate with investment data; not disaggregated by energy supply and end-use				from reference to mitigation scenario (500-550 ppmv CO_2-eq.)	various
(Edenhofer, Knopf et al. 2010)	1% to 2.5% loss of GDP					from reference to mitigation scenario (400 ppmv CO_2-eq.)	E3MG, IMAGE, MERGE, POLES, REMIND

Notes: Studies report investment needs differently, typically on a cumulative basis over long timescales (see 'Reported Investment Data' column). Here, annual investments are approximated to aid comparability using simple linear assumptions and adjusted to 2005$ using global GDP deflators; these annual estimates are indicative only and should not be attributed to the corresponding studies.

[a] Integrated assessment models vary widely in their structure, treatment of energy supply and demand, resolution of specific energy supply and end-use technologies, technology cost profiles over time, and so on. See corresponding references for details.
[b] Net decrease as lower overall energy supply investments due to demand reductions relative to reference scenario. In Hanson & Laitner (2006), energy supply total also includes systems integration costs.
[c] Reference scenario totals aggregate total investment in cars, and incremental investments in efficiency in other end-use technologies. Consequently, 94% of total investments in end-use technologies are in transport. See text for discussion and (Chapter 6, IEA 2008) for details.

2.3. Apples, Oranges, and End-Use Technologies

Certain characteristics of end-use technologies help explain their asymmetrical treatment in assessments of energy system investment costs. Firstly, end-use technologies are not traditionally considered to be energy sector investments, being rather a scatter of different industrial and consumer goods (Nakicenovic and Rogner 1996). Energy conversion – from the final user's perspective - is an often incidental attribute of end-use technologies whose primary purpose is to provide useful services such as lighting (lumens) and mobility (ton.kilometers of freight transport). Investment costs normalized to energy conversion capacity or use are therefore less meaningful.

Secondly, to ensure investment estimates for energy supply and end-use technologies are comparable, a common definition of the unit of analysis is needed. Investments in energy supply technologies are quantified at the level of the power plant, refinery or LNG terminal. What is the appropriate scale or system boundary of an end-use technology: carburetor, engine, car, or transport system? The one study shown in Table 1 which does estimate total end-use investments sidesteps this problem by combining total investments in cars with incremental investments in efficiency improvements in all other end-use technologies (IEA 2008). The rationale for this bounding of investment costs is that:

> *"energy efficiency improvements apply to a wide range of the car's components … [but] for building improvements, a breakdown of the costs of energy efficiency compared to the fabric or structure of a building would be arbitrary, while including the total construction cost would result in buildings taking up a disproportionate share of investment needs, when their primary role is shelter"* (Annex B, IEA 2008).

The resulting apples and oranges combination of total and incremental investments generates an estimate which is hard to interpret and unsurprisingly dominated by cars (see Table 1). It also points to the difficulties of clearly and consistently identifying what is being invested in. If the primary role of buildings is shelter, is the primary role of cars not mobility? In neither case are end-users investing directly in energy conversion.

Thirdly, investments in (and performance of) end-use technologies are dependent on investments in associated infrastructure such as airports, roads and buildings. Is it meaningful to quantify the investment cost of a home heating system without quantifying the investment cost of the home's building envelope which influences the heating load?

Although the same system boundary issue exists for energy supply technologies, it is largely addressed by additionally quantifying investment costs in associated transmission and distribution infrastructure. The problem for end-use technologies is that the same approach implies a summation of all investments in building structures, roads, railways, ports, airports, industrial machinery, and so on ad absurdum. But limiting the assessment of end-use technology investments to their efficiency improvements or mitigation potentials still leaves the problem of apples and oranges comparisons with energy supply technologies.

3. Method

3.1. Defining End-Use Technologies

Our response to the definitional issues with end-use technologies is to adopt two consistent but arbitrary definitions of end-use technology investments, and quantify total investments in each category. Our first, broader definition and data set describes end-use technologies as the technological systems purchasable as products by final consumers in order to provide a useful service (Murmann and Frenken 2006). This implies heating and air conditioning systems not houses, and fridges and ovens not kitchens. Our second, narrower definition and data set describes the specific energy-using components or subsystems of these end-use technologies. This implies engines in cars, and light bulbs in lighting systems. Table 2 summarizes these distinctions for the technologies analyzed. In some cases (industrial motors, mobile heating appliances), a distinct energy-using component was not identified and so the data in both cases are the same.

Table 2. Summary of End-Use Technologies & Their Energy-Using Components Included in Bottom-Up Investment Cost Estimates.

END-USE SERVICE	***BROAD DEFINITION:*** **END-USE TECHNOLOGY**	***NARROW DEFINITION:*** **ENERGY-USING COMPONENT OF END-USE TECHNOLOGY**
mobility	commercial jet **aircraft**	jet **engine**
mobility	**vehicles** (cars and commercial)	internal combustion **engine**
space conditioning	**central heating systems** (boiler/furnace, ducts/pipes, radiators, controls, & network connections for new systems)	**boiler** or furnace
space conditioning	**air conditioning systems** (AC unit, ducts, controls, & network connections for new systems)	**air conditioning unit**
space conditioning	**mobile heating appliances** (e.g., portable convection / fan heaters)	- (same as for end-use technology)
lighting	**lighting** (light bulb + fixture)	**light bulb** (or lamp)
food storage, cooking, cleaning	large **household appliances** (fridges, freezers, clothes washers & dryers, dish washers, cookers)	**compressors, motors, fans, heating elements** (depending on appliance)
industrial processes	**industrial motors**	- (same as for end-use technology)

3.2. Bottom-Up Estimation of Investment Costs

We used volume data (production, delivery, sales, installations) and cost estimates to approximate total investment costs in 2005 in both end-use technologies and their specific energy-using components (see below and Table 2 for details). We included low and high sensitivities around central estimates, taking account of uncertainties in both volume and cost assumptions.

Our aim is to provide a first order estimate of end-use technology investment costs to allow a meaningful, like-for-like comparison with estimates of energy supply technology investments. We acknowledge the many approximations and limitations in our data. We make all our data and sources openly available in an effort to stimulate further work in compiling and linking databases on end-use technologies, their volumes, costs, spatial distribution, and so on. Full details are available from the authors on request.

4. Results

Our first order estimate of total global investments in 2005 in end-use technologies is $1 - 3.5 trillion, with a central estimate of $1.7 trillion (see Figure 1). Our first order estimate of total global investments in the energy-using components of these end-use technologies is $0.1 – 0.6 trillion, with a central estimate of $0.3 trillion (see Figure 2).

We emphasize that these total investment estimates omit many end-use technologies, including: propeller-based and non-commercial aircraft, helicopters, all military technologies, mass transit systems, water heaters (residential and other), building envelopes (insulation, windows, doors), information and communication technologies, small appliances, other consumer electronics, and all industrial equipment and process other than motors (e.g., blast furnaces, pulp mills, cement kilns). With the exception of industrial plant and building envelopes, we believe the inclusion of these categories would not substantially increase the narrowly-defined investment cost range (for energy-using components); however, they would substantially increase the broadly-defined investment cost range (for end-use technologies).

Figure 1. Estimated Annual Investment In Selected End-use Technologies. Sources & data available from the authors on request.

End Use Technologies in 2005	**2005$**	*low sensitivity*	*central estimate*	*high sensitivity*	*share (central estimate)*
GRAND TOTAL COSTS	**$bn**	**984**	**1,739**	**3,549**	***100%***
commercial jet aircraft	$bn	*12*	***28***	*50*	***2%***
cars	$bn	*540*	***758***	*1,194*	***44%***
commercial vehicles	$bn	*270*	***427***	*672*	***25%***
buildings (retrofits) - central heating systems	$bn	*47*	***250***	*979*	***14%***
buildings (new) - central heating systems	$bn	*33*	***93***	*248*	***5%***
mobile heating systems	$bn	*2*	***4***	*5*	***0%***
buildings (retrofit) - air conditioning systems	$bn	*9*	***42***	*137*	***2%***
buildings (new) - air conditioning systems	$bn	*7*	***20***	*41*	***1%***
lighting	$bn	*17*	***38***	*83*	***2%***
large household appliances	$bn	*45*	***75***	*124*	***4%***
industrial motors	$bn	*2*	***6***	*16*	***0%***

Figure 2. Estimated Annual Investment In the Energy-Using Components of Selected End-use Technologies. Sources & data available from the authors on request.

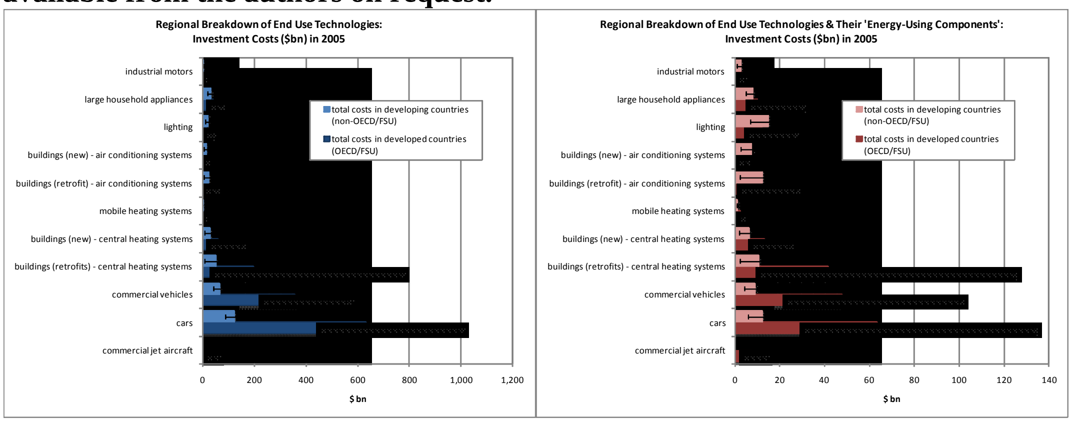
'Energy-Using Components' of End Use Technologies in 2005	**2005$**	*low sensitivity*	*central estimate*	*high sensitivity*	*share (central estimate)*
GRAND TOTAL COSTS	**$bn**	**124**	**297**	**713**	***100%***
commercial aircraft - jet engines	$bn	*3*	***7***	*13*	***2%***
cars - engines	$bn	*36*	***76***	*159*	***25%***
commercial vehicles - engines	$bn	*27*	***57***	*119*	***19%***
buildings (retrofits) - central heating units	$bn	*13*	***52***	*158*	***18%***
buildings (new) - central heating units	$bn	*9*	***20***	*41*	***7%***
mobile heating units	$bn	*2*	***4***	*5*	***1%***
buildings (retrofits) - air conditioning units	$bn	*5*	***21***	*69*	***7%***
buildings (new) - air conditioning units	$bn	*4*	***10***	*20*	***3%***
lighting	$bn	*12*	***27***	*59*	***9%***
large household appliances	$bn	*11*	***18***	*53*	***6%***
industrial motors	$bn	*2*	***6***	*16*	***2%***

Various observations can be made from the compiled data. First, the rank contribution of different technologies to total investment costs is broadly consistent regardless of the breadth of definition of end-use technologies. However, the proportionate cost of energy-using components to their corresponding end-use technology is lowest in vehicles. Second, transport technologies dominate both narrowly-defined and broadly-defined investments (but to a much lesser extent than in the IEA (2008) study shown in

Table 1 which mixed total and incremental investments). Third, more is invested in retrofitting heating and cooling technologies than in new building installations, reflecting the longevity of buildings and the more pervasive penetration of mechanical space conditioning technology in developed countries. Fourth, technologies providing mobility and space conditioning account for over four fifths of total investment costs, again regardless of whether narrowly- or broadly-defined (though reaching as high as 92% of total investments in the latter case).

Disaggregating the data by region shows that approximately two thirds of the end-use investments costs in 2005 are in OECD countries and the former Soviet Union (FSU), broadly corresponding to IEA countries. The remaining one third are in developing economies (see Figure 3). However, investment data for aircraft and vehicles is by region of manufacture not final use (and purchase) which inflates the developed country shares of these technologies.

Figure 3. Annual Investment By Region In End-Use Technologies (Left-Hand Graph) and their Energy-Using Components (Right-Hand Graph). Sources & data available from the authors on request.



5. Discussion: The (Relative) Importance of Investments in End-Use Technologies

The range of end-use technology investments is conservatively in the order of $0.3 – 4.0 trillion, adjusting upwards the range of $0.1 - 3.5 trillion to take into account the extent of technologies missing from this analysis. This compares with the range of current energy supply investments in the order of $0.7 – 0.9 trillion. Although the two ranges span the same orders of magnitude, the upper bound of end-use technology investment costs is some 4 times greater than its energy supply equivalent. This is in line with the IEA's findings that demand-side investment needs are four times those of the energy supply alone (p227, IEA 2008). It is also in line with the one study we found in our review which quantified total investments consistently for different end-use technologies, and estimated "total efficiency investments" in the US to be three times larger than those in the energy supply (Ehrhardt-Martinez and Laitner 2008).

Estimating total diffusion investments in end-use technologies relative to those in the energy supply is important to understand the financial needs and magnitudes of energy system transformation. It also provides a common and consistent reference point for international policy making and diplomacy in the context of climate change mitigation (Bazilian, Nussbaumer et al. 2010) and associated analysis of financing needs and investment flows (UNFCCC 2007).

To the extent that total investment estimates are granular, i.e., resolved at the level of individual technologies, a like-for-like comparison of total end-use and total energy supply investments also supports assessments of specific financing implications for different sources of investment (e.g., balance sheets, capital markets, disposable household income) and types of investor (e.g., households, firms, governments). Recognizing the importance of investors and sources of capital from outside the traditional energy sector is particularly important. The UK's Committee on Climate Change, for example, only considers the incremental capital needs of the building stock to be investments if financed via energy companies (p145, UK_CCC 2010). The IEA calls the change in thinking and structure needed to focus on investments in end-use technologies "a paradigm shift" (p223, IEA 2008). This is a longstanding view:

> "[Traditional definitions of energy investment] *do not include investment in end-use technologies, such as furnaces, appliances and vehicles, because they are traditionally counted as durable consumer goods or business investments. However, the fact that the performance of end-use technologies plays such an important role … is a strong argument in favour of new approaches to evaluating energy sector investment*" (p9, Nakicenovic and Rogner 1996).

The importance of 'diffusion' investments in end-use technologies also warrants a more granular treatment in energy system and climate change mitigation analyses. In particular, like-for-like comparisons of financing requirements for both energy supply and end-use technologies avoid the risk that scenarios relying heavily on efficiency improvements and end-use technology investments appear less costly than scenarios relying heavily on decarburization and energy supply technology investments. This appearance can be an artifact of the way in which total investments in energy supply technologies are compared with incremental investments in end-use technologies. This is straightforwardly misleading. In other cases, end-use technology investments are not estimated in any form (see Table 1). If total investments for both energy supply and end-use technologies cannot be compared, then the use of incremental investments should be consistently applied. So total investments in energy supply technologies should be net of foregone investments from the reference scenario (see Luderer, Bosetti et al. 2009 for an example).

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