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Environmental sustainability of cooking fuels in remote communities: Life cycle and local impacts



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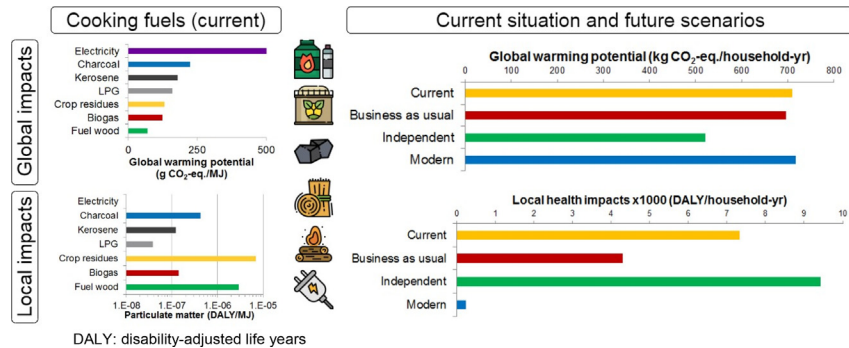
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HIGHLIGHTS

- This is a first study of life cycle and local impacts of cooking in remote communities.
- Current situation and 2030 scenarios are considered for the South-Asia Pacific region.
- Electricity from diesel is the worst and biogas from manure is the best option.
- Biomass fuels have up to 47 times lower life cycle but 4–23% higher local impacts.
- A mix of LPG, biogas and renewable electricity has the lowest overall impacts.

GRAPHICAL ABSTRACT



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ABSTRACT

Access to clean cooking fuels and technologies is essential for achieving the Sustainable Development Goals, particularly in developing countries, to minimise human health and environmental impacts. This paper assesses for the first time the environmental sustainability of household cooking, focusing on remote communities in developing countries in the Southeast Asia-Pacific (SEAP) region and considering both life cycle and local impacts. To guide rural development policies, the impacts of the following cooking fuels are considered: liquefied petroleum gas, kerosene, wood, charcoal, crop residues, biogas and electricity. Both the present situation and three future (2030) scenarios are evaluated on 18 life cycle impacts, as well as on local environmental and health impacts caused by cooking. The results show that electricity is the worst option in 13 out of 18 life cycle categories since it is generated from diesel in off-grid communities. Biogas from manure is the best fuel with 16 lowest life cycle impacts. Biomass fuels can have lower life cycle impacts than fossil fuels but they have high combustion emissions which lead to higher local environmental and health impacts. Future scenarios with higher biomass utilisation have up to 47 times lower life cycle impacts than at present, but 4–23% higher local impacts. Health impacts related to fuel combustion are higher in Vietnam, the Philippines, Cambodia, Laos and Myanmar compared to the other SEAP countries due to regional background pollutant concentrations and health trends. A fuel mix with liquefied petroleum gas, biogas and renewable electricity offers considerable reductions in 13 life cycle impacts compared to the present situation, while also reducing local health impacts by 78–97%. A self-sufficient fuel mix with local biomass and renewable electricity would reduce 17 out of 18 life cycle impacts, but all local impacts, including on health, would be 11–28% higher than at present. The results from this study can be used by policy makers and other stakeholders to develop policies for clean cooking in remote communities and reduce both environmental and human health impacts.

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Nomenclature

1,4-DB	1,4-dichlorobenzene
AD	Anaerobic digestion
ALOP	Agricultural land occupation potential
DALY	Disability-adjusted life years
eq.	Equivalent
FDP	Fossil depletion potential
FEP	Freshwater eutrophication potential
FETP	Freshwater ecotoxicity potential
GHG	Greenhouse gases
GLO	Global weighted average characterisation
GWP	Global warming potential
HTP	Human toxicity potential
IDN	Indonesia, Papua New Guinea, East Timor
IRP	Ionising radiation potential
LCA	Life cycle assessment
LPG	Liquefied petroleum gas
m ² a	m ² year
MDP	Mineral depletion potential
MEP	Marine eutrophication potential
METP	Marine ecotoxicity potential
MYS	Malaysia, Singapore, Brunei
NLTP	Natural land transformation potential
NMVOC	Non-methane volatile organic compounds
ODP	Ozone depletion potential
PAC	Pacific Islands, Papua New Guinea
PHL	Philippines
PM10	Particulate matter (<10 µm)
PMFP	Particulate matter formation potential
POFP	Photochemical oxidant formation potential
RSEA	Cambodia, Laos, Myanmar
TAP	Terrestrial acidification potential
TETP	Terrestrial ecotoxicity potential
THL	Thailand
ULOP	Urban land occupation potential
VNM	Vietnam
WDP	Water depletion potential

1. Introduction

In household energy assessment, non-electricity energy use can go unnoticed especially in countries where space heating is not needed. Data indicate that electricity represents only 17% of the residential energy consumption in non-OECD countries, second to biomass (48%) (International Energy Agency, 2018a). For example, 76% of household energy use in the Philippines is derived from biomass and cooking fuels (Philippine Statistics Authority, 2017). Despite this significant contribution, household cooking is not included in national energy plans (Philippine Department of Energy, 2016a). This is a concern because providing modern and sustainable energy includes access to clean fuels and technologies for cooking, referred to as “clean cooking” (Angelou et al., 2013).

Clean cooking is essential in achieving the Sustainable Development Goals (SDG) – not only for affordable and clean energy, but also for public health, gender equality and environmental impacts (UNDP, 2017). As an SDG indicator, clean cooking is evaluated in terms of both the fuels and the stove used. The use of kerosene and solid biomass (e.g. wood) in traditional cooking stoves is not deemed clean cooking as these are major sources of indoor air pollution (International Energy Agency, 2018b). The use of solid biomass fuels is linked to greater incidence of respiratory diseases, especially with vulnerable populations in rural areas (Capuno et al., 2018; Liu et al., 2018). Deforestation and time needed for collection are further impacts of the reliance on traditional

biomass as a cooking fuel. Yet, these are still the predominant cooking fuels used in developing countries (International Energy Agency et al., 2019). The fuels that are considered “clean” are biogas, liquefied petroleum gas (LPG), electricity and natural gas (Angelou et al., 2013). However, these are available only to a small fraction of households in developing countries and are less common in rural regions (International Energy Agency et al., 2019). Advances in clean cooking also consider improved cooking stoves which have higher efficiencies and better control of particulates (Global Alliance for Clean Cookstoves, Eastern Research Group, 2017).

Progress towards universal access to clean cooking is positive, but not on track to meet the SDG. It is projected that 2.3 billion people will remain reliant on traditional biomass for cooking in 2030, 65% of whom will be in Asia and 80% of that in rural areas (International Energy Agency and World Bank, 2017). Hence, there is a need to accelerate clean cooking programmes particularly in rural areas in Asia. However, constrained supply and distribution of clean fuels and technologies represent a challenge against a backdrop of abundant (and often free) biomass in remote communities (UN-ESCAP, 2017). The lack of priority in high-level energy planning is also a barrier towards comprehensive implementation and management of clean cooking.

The environmental impacts of cooking in remote communities and transition to clean cooking have been studied previously for other developing regions but not for Southeast Asia. For example, a life cycle assessment (LCA) study in Ghana found that biogas had advantages in many impact categories, but LPG had the lowest contribution to climate change if traditional biomass fuels were not considered to be carbon neutral (e.g. unsustainable forestry) (Afrane and Ntiamoah, 2011). Another study in India recommended biogas and charcoal as sustainable options based on LCA findings (Singh et al., 2014). An assessment of the household cooking sector in Nigeria found that a business-as-usual future would result in four times higher environmental impacts compared to the current situation (Gujba et al., 2015). A more recent report compared cooking fuel systems in India, China, Kenya and Ghana finding that human health risks, mainly from particulate matter formation, are strongly sensitive to projected future fuel mixes (Morelli et al., 2017). However, as LCA focuses on the entire life cycle of products and processes, studies of cooking do not explicitly address the difference in impacts occurring locally and elsewhere in the life cycle. As mentioned previously, local impacts, particularly on health, can be critically important in cooking systems and would benefit from further investigation.

Therefore, this study investigates for the first time both the life cycle and local environmental and health impacts of household cooking in remote rural communities, focusing on the Southeast Asia-Pacific (SEAP) region. Specifically, the objectives are (i) to evaluate the impacts of current cooking fuels in remote communities; and (ii) to develop future “clean cooking” scenarios and identify environmentally the most sustainable options in comparison with the current situation. The future scenarios, defined based on different development trajectories to 2030, and the current situation are evaluated using the LCA framework. Local health impacts are analysed through regionalised impact assessment of emissions generated during the use of cooking fuels. The results from this work can help guide rural development policies, aiming to facilitate a transition towards clean cooking in developing regions.

The next section describes the methods used for LCA and regionalised impact assessment for local emissions. The results are presented and discussed in Section 3, firstly for the life cycle and then for local impacts. The key conclusions and stakeholder recommendations are summarised in Section 4.

2. Methods

The life cycle environmental impacts of cooking fuels have been estimated according to the guidelines in ISO 14040/44 (ISO, 2006a; ISO, 2006b), following the attributional approach. System modelling and

calculations of impacts have been carried out in GaBi ts 7.3 (Thinkstep, 2016). The following sections describe the LCA methodology, including the goal and scope of the study, inventory data and the impact assessment method used to estimate the impacts.

2.1. Goal and scope

The main goal of this study is to estimate the life cycle environmental and local health impacts of fuels used for household cooking in remote communities typically found in Southeast Asia and small island developing states in the Pacific. Another objective is to identify opportunities for improvements compared to the current situation by considering feasible future scenarios for household cooking. In alignment with the timeline for the SDG, the future scenarios have been developed for the year 2030.

The fuels included in the study are those that are used currently in developing countries, i.e. fuel wood, charcoal, crop residues, kerosene and LPG. Clean fuels that could become more available in the future, such as biogas and electricity, are also considered. The impacts of current traditional and future improved cooking stoves are also included in the study. For both the fuels and stoves, the system boundary is from cradle to grave, as indicated in Fig. 1.

Based on the above-mentioned goals of the study, two functional units are considered:

- i) for the environmental impacts of individual fuels: ‘1 MJ delivered by the cooking stove’; and
- ii) for the environmental impacts of the current fuel mix and future scenarios: ‘annual cooking energy demand of 5 GJ per household’, based on annual cooking requirements of a family of five in developing countries (O’Sullivan and Barnes, 2007).

2.2. Inventory data

The data for the fuels and their current supply mix are based on the conditions of remote rural communities in the Philippines (Philippine Statistics Authority, 2013). The Philippines is chosen as a representative

location since a high proportion of its population lacks access to clean cooking, relative to both the regional and global situation (International Energy Agency, 2018b). The next two sections detail the data and assumptions for the fuels and the stoves, respectively, followed by an overview of the current situation and future scenarios.

2.2.1. Fuels

For the fossil fuels, data on the extraction of oil and gas and their refining have been sourced from the ecoinvent 3.1 database (Ecoinvent Association, 2014). Transportation of the refined fuel has been modelled based on the supply profile of the Philippines (UN Statistics Division, 2017) by taking into account the average distances travelled from the major exporting countries (Table 1). Bottling and distribution of LPG has been modelled based on literature data (Singh et al., 2014; Jungbluth, 1997), while extraction and production processes for kerosene are from ecoinvent (Ecoinvent Association, 2014).

Fuel wood is assumed to be collected by local residents from forest residues and hence transportation is negligible. As waste, forest residue is considered to have no environmental impacts associated with its cultivation. It is also assumed that forest residues are harvested at a sustainable rate and that virgin wood is not used. Assessments of forest use in the Philippines support the assumption that fuel wood collection does not exceed sustainability limits of the resource (FAO, 2015; Drigo et al., 2014). Charcoal is produced with a 30% yield by heating the same type of forest residue wood in a kiln, releasing condensable matter (Singh et al., 2014). Solid waste from this carbonisation process is landfilled (Singh et al., 2014). The inventory data for charcoal production have been sourced from Singh et al. (2014).

Rice and coconut are the most produced crops in SEAP (Food and Agriculture Organization, 2017) and may be assumed as the representative crops for many rural locations. Residues usable as cooking fuel are rice straw and husks, as well as coconut shells and husks. Except for rice straw, the crop residues are taken as waste and, like forest residues, have no environmental impacts associated with crop cultivation. Rice straw is currently either burned in fields or used as mulch (Gadde et al., 2009). Hence, the utilisation of rice straw as a cooking fuel has been credited for the avoided impacts of field burning; the data for

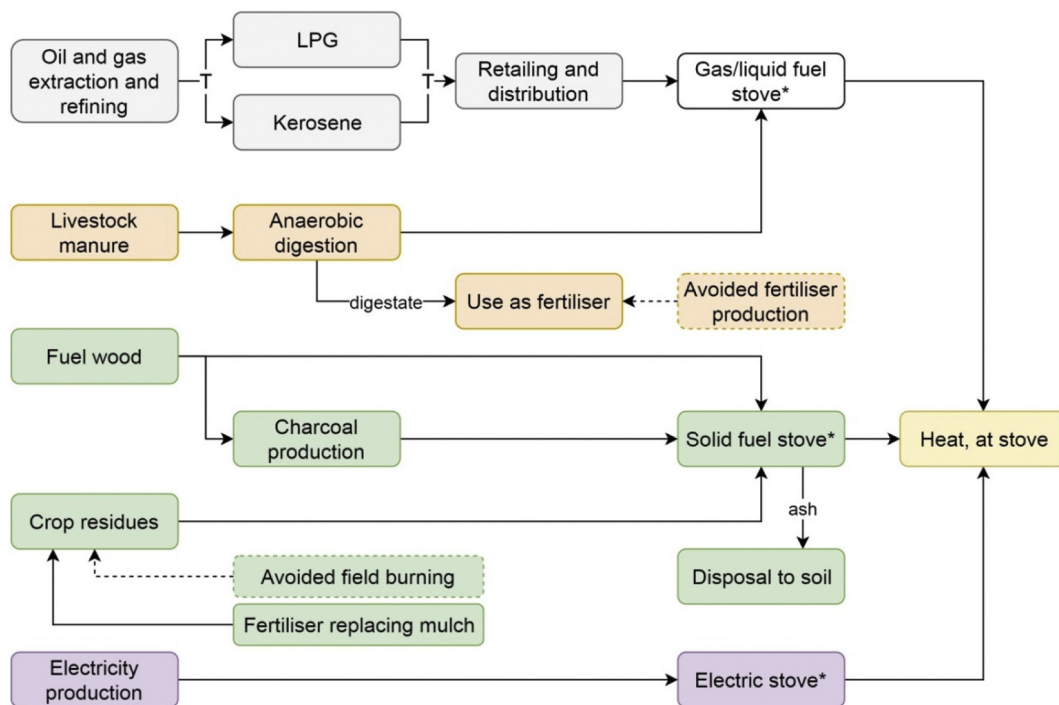


Fig. 1. System boundaries for the cooking fuels in this study. (*The life cycle stages for the stove comprise raw materials production, assembly, use and end-of-life waste management. The dashed lines represent system credits. T: transport.)

Table 1
Import and transportation of fossil fuels in the Philippines in 2017 (UN Statistics Division, 2017).

Fuel	Fraction imported	Import distance (average), km	Transportation mode
LPG	65%	5700	Freight, sea, liquefied natural gas
Kerosene	29%	1970	Freight, sea, transoceanic tanker

Table 2
Heating value and stove efficiencies for various cooking fuels (Singh et al., 2014; Morelli et al., 2017; Phichai et al., 2013; Chungsangunsit et al., 2005).

Fuel	Heating value	Efficiency of current stoves	Efficiency of future stoves
LPG	45.24 MJ/kg	49%	57%
Kerosene	42.86 MJ/kg	46%	52%
Fuel wood	9542 MJ/m ³	11%	19%
Charcoal	27.41 MJ/kg	14%	25%
Crop residues	16.27 MJ/kg	11%	22%
Biogas	19.60 MJ/m ³	55%	57%
Electricity	3.60 MJ/kWh	59%	80%

the latter are from Chang et al. (2013). However, additional impacts from mineral fertilisers needed to replace the mulch are also included, based on the equivalent nutrient content in the mulch. Since the context of the study assumes local utilisation, transportation of the crop residues is negligible. Further details on the respective characteristics of the crop residues and their post-combustion ash can be found in Tables S1 and S2 in the Supplementary information (SI).

Despite the industrialisation of livestock farming, backyard farms in developing countries are expected to remain in business in the foreseeable future (Delgado et al., 2008). Therefore, livestock manure could be used to produce biogas as cooking fuel which is considered in future scenarios. It is assumed that manure from cattle, chickens and pigs is diverted from various disposal methods (see Table S3 in the SI) and fed to a backyard-scale anaerobic digester. The digestate is collected and assumed to be used on the farm, replacing mineral fertilisers. The system has been credited for the latter in proportion to the nutrient content of the digestate. Emissions from the digester, as well as digestate storage and application have been sourced from the literature (De Vries et al., 2012). Further details on the biogas production are provided in Tables S4 and S5 in the SI.

Electricity is currently seldom available in remote communities (Philippine Department of Energy, 2016b) and it is generated using diesel generators (note that diesel is not used as a fuel in cooking stoves but

instead kerosene is utilised, as discussed earlier). The LCA impacts of diesel electricity have been sourced from a previous study (Aberilla et al., 2020). The infrastructure for the power system is based on the literature (Ecoinvent Association, 2014; Benton et al., 2017; Kabir et al., 2012; Spanos et al., 2015), but the energy output has been determined through microgrid simulations (Aberilla et al., 2020) in HOMER Pro (HOMER Energy LLC, 2017) (see Table S6 in the SI).

2.2.2. Stoves

Material inventories for cooking stoves have been obtained from previous studies (Jungbluth, 1997; Wilson et al., 2016), with gas/liquid fuel stoves assumed to last 15 years and the other types 5 years. Stoves are expected to supply the annual cooking heat demand of 5 GJ per household (O'Sullivan and Barnes, 2007). Ferrous metals, aluminium and copper are assumed to be recycled at rates of 39%, 47% and 44%, respectively, based on average recycling rates in the Philippines (JICA, EX Corporation, 2008; Glöser et al., 2013); the remainder is landfilled. As the recycled materials count towards the recycled fraction of materials used in manufacturing at the respective rates of 10%, 19% and 34% (BIR Ferrous Division, 2016; Tse, 2015), the system has been credited for the balance for avoiding primary production, i.e. for 29% of steel, 28% of aluminium and 10% of copper. For details, see Fig. S1 in the SI.

Heating values and thermal efficiencies for both current (traditional) and future (improved) stoves are summarised in Table 2 (Singh et al., 2014; Morelli et al., 2017; Phichai et al., 2013; Chungsangunsit et al., 2005). As indicated, stove efficiencies vary because different fuels require different stove designs. Emissions from the combustion of the fuels are based on the literature (Singh et al., 2014). Ash from the combustion of solid biomass is assumed to be disposed to non-agricultural soil (backyard), with the impacts to soil estimated based on the ash composition (Table S2 in the SI).

2.2.3. Current fuel mix and future scenarios

Three 2030 scenarios are considered, alongside the present fuel mix, as follows (Fig. 2):

1. Current situation: The current fuel mix is based on the latest energy consumption survey in the Philippines (Philippine Statistics Authority, 2013). The most commonly used fuels are LPG (39.8%) and fuel wood (30.9%), followed by charcoal (15.3%) and crop residues (9.6%). The last comprises 68.3% coconut husk, 31.1% coconut shell, 0.4% rice husk and 0.2% rice straw (Table S1). Kerosene is also used but at a lower rate (4.4%); biogas and electricity are not utilised at present.

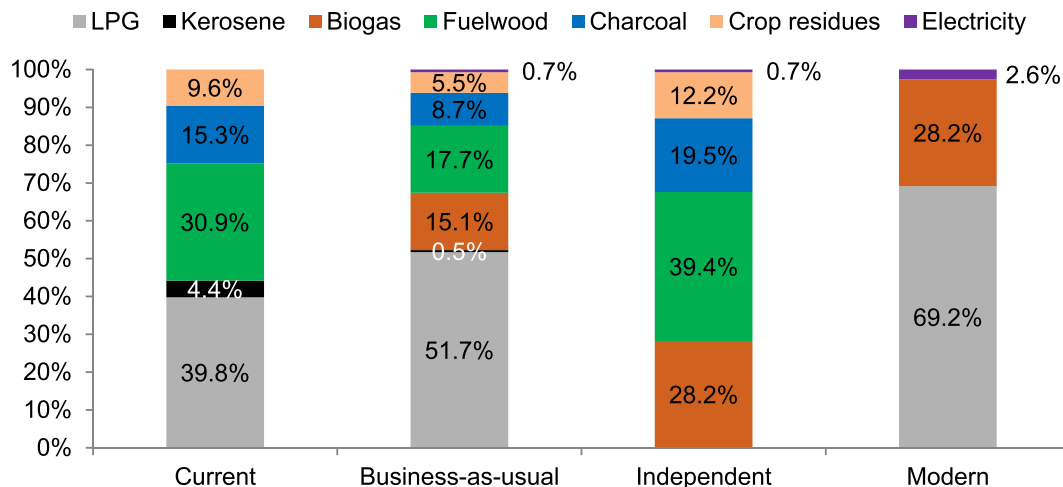


Fig. 2. Household cooking fuel mix for the current situation and 2030 scenarios.

2. Business-as-usual (BAU): The BAU scenario is based on past and current trends in cooking energy use. It is expected that LPG use will increase by 30% by 2030 while shares of traditional biomass will decrease by 43% (OECD/IEA, 2017). Conversely, kerosene use is assumed to decrease at its historical rate of 13% year on year (United Nations, 2016), contributing only 0.5% to the fuel mix by 2030. The share of crop residues falls to 5.5%, with the same share of different types as for the current situation. It is also projected that 12% of household electricity consumption will be used for cooking (OECD/IEA, 2017) in 2030. Taking into account the efficiency of electric stoves (80%), this means that only 0.7% of the annual cooking demand will be supplied by electricity, all of which is generated from diesel in this scenario. The remaining demand (15.1%) is then assumed to be satisfied by biogas.
3. Independent: This scenario assumes that all cooking fuels will be supplied from local resources, i.e. there is no import of LPG and kerosene. Consequently, biogas production from livestock manure is maximised (28.2%), assuming a proportional increase in traditional biomass use, with fuel wood contributing 39.4%, charcoal 19.5% and crop residues 12.2%. The latter has the same residue shares as the current situation. The remaining 0.7% is supplied by electricity, as in BAU, but here it is generated by solar PV (83%) and wind turbines (17%). The LCA impacts of this electricity mix have been sourced from the authors' previous study (Aberilla et al., 2020).
4. Modern: This scenario describes a future household wherein only clean fuels are used. For this reason, biogas utilisation is maximised (28.2%), together with electricity (2.6%), the latter on the basis of increased access to electricity (Bhatia and Angelou, 2015). The electricity is generated from solar PV (75%), wind (18%) and diesel (7%). The remainder of the demand (69.2%) is satisfied by LPG.

2.3. Life cycle impact assessment

The ReCiPe 1.08 method (Goedkoop et al., 2013) has been used to estimate the impacts, based on the hierarchist approach. All 18 midpoint indicators in the ReCiPe method are considered in the study. To streamline the discussion in the next section, they are grouped into eight environmental issues, as follows:

- climate change: global warming potential (GWP); biogenic CO₂ is excluded;
- air pollution: ozone depletion (ODP), photochemical oxidant formation (POFP) and particulate matter formation potentials (PMFP);
- eutrophication and acidification: freshwater and marine eutrophication potentials (FEP and MEP, respectively) and terrestrial acidification potential (TAP);
- ecotoxicity: freshwater, marine and terrestrial ecotoxicity potentials (FETP, METP and TETP, respectively);
- resource depletion: fossil, mineral and water depletion potentials (FDP, MDP and WDP, respectively);
- land use: agricultural land occupation (ALOP), natural land transformation (NLTP) and urban land occupation potentials (ULOP); and
- human health: human toxicity (HTP) and ionising radiation potentials (IRP).

For the estimation of local health impacts, locally-regionalised end-point characterisation factors have been applied to the emissions from the cooking stoves to estimate particulate matter (PMFP) and oxidant (ozone) formation (POFP) (van Zelm et al., 2016). These two impact categories have damage pathways that are spatially-dependent and occur in short time horizons (van Zelm et al., 2016); hence, they are relevant for the study of local health impacts. Six regions representing the whole of Southeast Asia plus one region representing small island developing states in the Pacific are considered (van Zelm et al., 2016):

- Indonesia, Papua New Guinea and East Timor (IDN);
- Malaysia, Singapore and Brunei (MYS);
- Pacific Islands and Papua New Guinea (PAC);
- Philippines (PHL);
- Cambodia, Laos and Myanmar (RSEA);
- Thailand (THL); and
- Vietnam (VNM).

The results obtained with local characterisation factors, as well as with the global weighted-average value ("GLO"), are used to investigate the variability in fuel rankings with geographical location in terms of their impacts, as well as to identify regions that may be more vulnerable to the health impacts of cooking.

3. Results and discussion

This section first compares the environmental impacts of the cooking fuels. This is followed by the evaluation of the current situation and future scenarios and, finally, by the local health impacts of fuel use.

3.1. Life cycle impacts of fuels

The impacts of the cooking fuels are compared in Fig. 3, with the contributions by life cycle stage provided in Fig. S2 in the SI. Overall, electricity from diesel has the highest impacts in 13 categories. In contrast, biogas has the lowest impacts in 16 categories, mainly due to the credits for the utilisation of manure. Further discussion of the environmental impacts follows.

3.1.1. Climate change (GWP)

Greenhouse gas (GHG) emissions from the diesel generator are the main reason for electricity having the highest GWP (502 g CO₂ eq./MJ). Charcoal has the second highest impact (225 g CO₂ eq./MJ), of which 80% is due to the carbonisation process. This is followed by kerosene (179 g CO₂ eq./MJ) and LPG (160 g CO₂ eq./MJ), largely due to the combustion emissions of CO₂. Crop residues have a slightly higher GWP than biogas (132 and 124 g CO₂ eq./MJ, respectively). Finally, fuel wood is the best option for this impact (70 g CO₂ eq./MJ), which is seven times lower than that of electricity. For solid biomass fuels, methane is the main GHG, emitted during incomplete combustion (Smith et al., 2000). In the case of biogas, the impact is due to nitrous oxide emitted from application of the digestate. The contribution of the stoves is negligible, as also found in another study (Wilson et al., 2016).

3.1.2. Air pollution (ODP, PMFP, POFP)

Biogas is the preferred option with the lowest impacts in all three air pollution categories. This includes net negative values in ODP and PMFP due to the use of digestate as a fertiliser. Electricity from diesel is the worst option for ODP because of halon emissions from refrigerants used in refinery operations. This is also the reason for the high ODP of LPG and kerosene. Crop residues have the largest PMFP due to the particulates emitted during their combustion in the stove. Finally, POFP is the highest for charcoal because of carbon monoxide and ethane emitted during its production.

3.1.3. Eutrophication and acidification (FEP, MEP, TAP)

As shown in Fig. 3, biogas ranks the best in all three categories, with net negative impacts due to the avoided fertiliser production associated with the digestate use. The solid biomass options (fuel wood, charcoal and crop residues) have the highest FEP, with charcoal being the worst option. This is related to the release of phosphorus from the ash disposal to soil. Cooking with electricity has the highest MEP and TAP, with most of the contribution attributed to the emissions from diesel during power generation. Nitrous oxide emissions during the

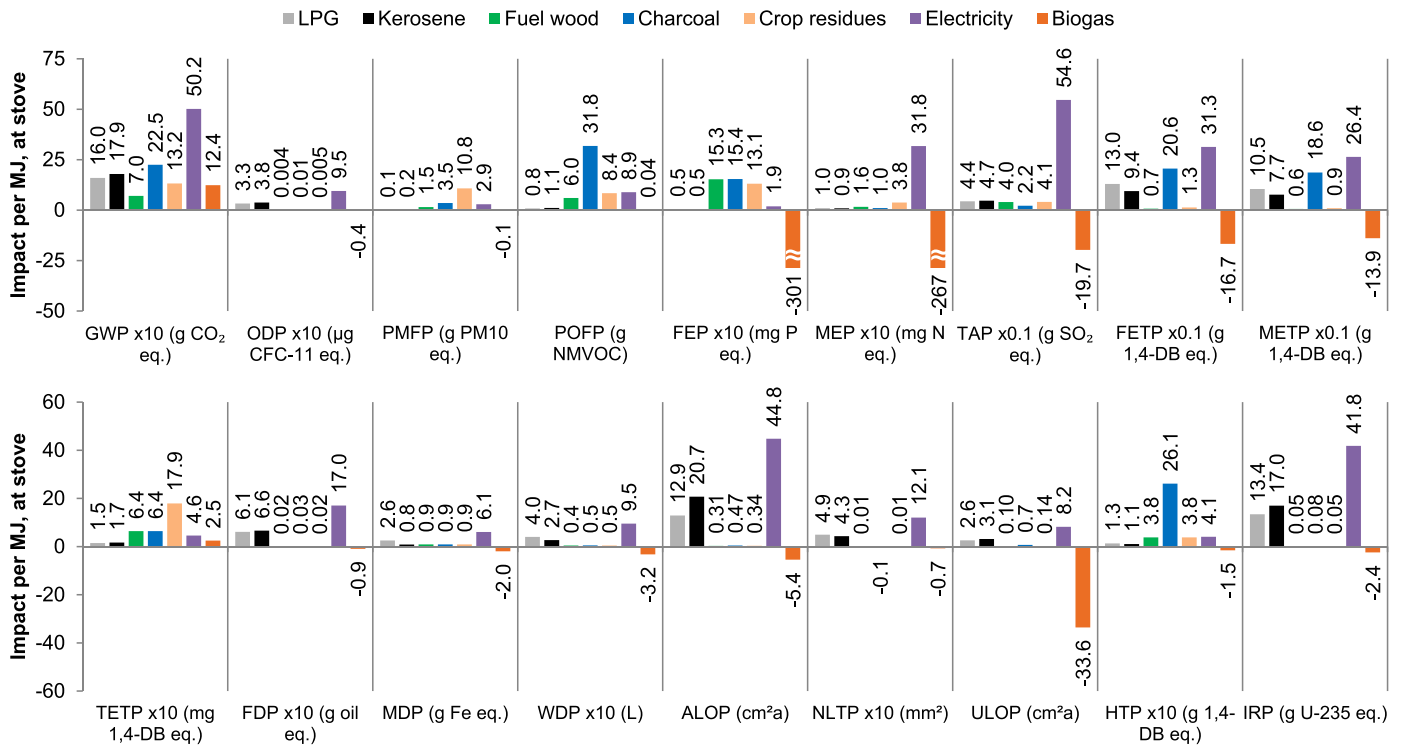


Fig. 3. Life cycle environmental impacts of current cooking fuel options. [All impacts are expressed per MJ] of heat at stove. Electricity is generated from diesel. Crop residues comprise 68.3% coconut husk, 31.1% coconut shell, 0.4% rice husk. And 0.2% rice straw. Data labels are cradle-to-grave totals to be multiplied by factors on the x-axis where relevant. GWP: global warming potential; ODP: ozone depletion potential; PMFP: particulate matter formation potential; POPF: photochemical oxidant formation potential; FEP: freshwater eutrophication potential; MEP: marine eutrophication potential; TAP: terrestrial acidification potential; FETP: freshwater ecotoxicity potential; METP: marine ecotoxicity potential; TETP: terrestrial ecotoxicity potential; FDP: fossil depletion potential; MDP: mineral depletion potential; WDP: water depletion potential; ALOP: agricultural land occupation potential; NLTP: natural land transformation potential; ULOP: urban land occupation potential; HTP: human toxicity potential; IRP: ionising radiation potential]

combustion of solid biomass also result in comparatively high MEP. LPG and kerosene have a comparable but slightly higher TAP than fuel wood and charcoal, with the main source being SO₂ emissions in the refining process.

3.1.4. Ecotoxicity (FETP, METP, TETP)

Aquatic ecotoxicity (FETP and METP) is the highest for electric cooking due to the zinc content of effluents from diesel refining. Charcoal is the second worst fuel for FETP and METP due to the manganese content in ash that leaches to water during disposal. As with the previous categories, biogas has the lowest FETP and METP due to the credits for digestate. For TETP, crop residues (especially coconut shells) have the highest impact, primarily due to trace metals in the ash, such as copper, nickel and barium. Trace metals are also the main contributors (>98%) to the TETP of other biomass fuels, including biogas. As a result, LPG and kerosene have the lowest TETP among the fuel options.

3.1.5. Resource depletion (FDP, MDP, WDP)

Using electricity for cooking has the highest resource depletion impacts in all three categories due to the diesel. Similar applies to LPG and kerosene which also have high impacts. In contrast, the resource depletion impacts of solid biomass are related to the stove construction. Biogas remains the preferred option in these categories due to credits for displaced fertilisers.

3.1.6. Land use (ALOP, NLTP, ULOP)

Electricity is the worst alternative in the three land use categories and biogas the best, with net-negative impacts (Fig. 3). Fossil-fuel based options (electricity, LPG and kerosene) have significantly higher land use than biomass fuels due to the associated upstream processing of crude oil and (waste) biomass having no upstream impacts.

3.1.7. Human health (HTP, IRP)

Charcoal has the highest HTP with 85% of the impact attributed to manganese leaching to water from solid wastes in the carbonisation process. Trace metals in the ash of other solid biomass residues cause almost all of their HTP (98%). Electricity has the highest IRP which is due to C-14 emissions from diesel refining. Comparable levels of IRP are also seen in the other fossil fuels due to similar upstream processes. For both HTP and IRP, biogas has the lowest impacts, which are again due to credits for displacing mineral fertilisers.

3.1.8. Comparison of results with previous studies

Fig. 4 compares the results obtained in this research with similar work carried out for other regions (Morelli et al., 2017). It can be seen that the current results are within an order of magnitude of most of the values reported for other regions. The differences between the studies are primarily due to the specific conditions in each region, such as the electricity mix, supply chains and local deforestation rates, as well as differing methodologies and assumptions (e.g. system boundaries and characterisation factors). Morelli et al. (2017) also assumed that refinery operations use alternative halons which have greatly lower ODP. Furthermore, they only considered cattle dung as the feed for biogas production and used a cut-off allocation method – hence, the significant difference in life cycle impacts relative to this study.

3.2. Life cycle impacts of current fuel mix and future scenarios

The three future cooking scenarios are compared with the current situation in Fig. 5. The results suggest that the ‘independent’ scenario is the best option, reducing significantly (up to 47 times) all impacts but TETP compared to the current situation, including GWP. This scenario also has eight net-negative impacts, such as ODP, MEP, TAP and

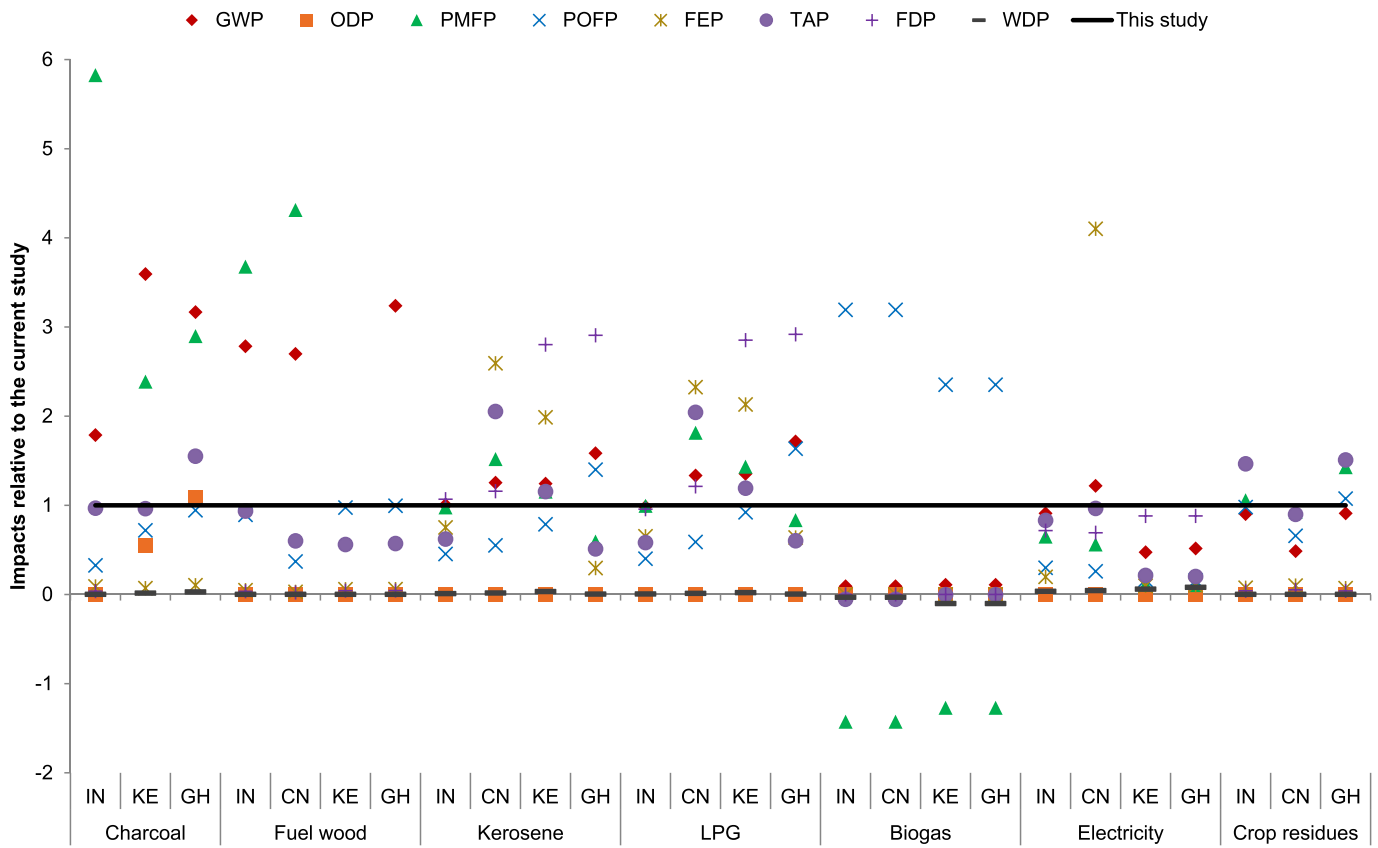


Fig. 4. Comparison of results with studies for other regions (Morelli et al., 2017). [The impacts in other studies have been scaled relative to the impacts obtained in the current study. All impacts are expressed per MJ. IN: India, CN: China, KE: Kenya, GH: Ghana. For impact nomenclature, see Fig. 3.]

ULOP. Compared to the BAU and ‘modern’ scenarios, it has the lowest impacts in 11 categories, including GWP.

The next best option is the ‘modern’ scenario which reduces 13 impacts on the current situation. Relative to the other scenarios, it is the best option for seven impacts, four of which are net-negative. However, it is also the worst scenario for five categories, including GWP, which is slightly higher than at present.

The BAU scenario reduces 11 impacts in comparison to the present fuel mix, including GWP and it has three net-negative impacts (FEP, MEP and ULOP).

These results are discussed further below, all expressed per household per year and referring to the annual cooking energy demand of 5 GJ.

3.2.1. Climate change (GWP)

For the current fuel mix, the GWP is estimated at 711 kg CO₂-eq., with 45% attributed to LPG. The BAU scenario offers only a 2% reduction in GWP as the introduction of low-carbon biogas is counteracted by the increased fraction of LPG. The ‘independent’ scenario has 27% lower impact than the current fuel mix as LPG and kerosene are replaced by biogas and electricity from renewables. A slight increase (1%) in the impact is seen in the ‘modern’ scenario following a significant rise in LPG use, counteracted by credits for displacement of mineral fertilisers associated with biogas.

3.2.2. Air pollution (ODP, PMFP, POFP)

LPG accounts for 88% of the ODP in the current situation (75 mg CFC-11 eq.). Hence, with the higher LPG use in the BAU and ‘modern’ scenarios, ODP increases in these scenarios. In contrast, maximised biogas use in the ‘independent’ scenario results in a net negative ODP. For PMFP and POFP, all future scenarios show an improvement

against the current situation, with the ‘modern’ being the best option. In the current situation, crop residues and charcoal account for more than half of the annual PMFP and POFP impacts. Therefore, the reduced use of these fuels in the BAU and ‘modern’ scenarios explains the decrease in these impacts. In the ‘independent’ scenario, while the share of solid biomass in the mix is higher, the biogas credits are sufficient to lead to a net decrease in the PMFP and POFP compared to the present day.

3.2.3. Eutrophication and acidification (FEP, MEP, TAP)

Fuel wood is a major contributor (32–55%) to eutrophication and acidification in the current fuel mix. LPG also accounts for a significant share of MEP (27%) and TAP (44%). All future scenarios show large reductions in these impact categories, primarily due to the credits in the biogas system for the displacement of mineral fertilisers. With the exception of TAP in the BAU scenario, the FEP, MEP and TAP are net negative and highlight the positive effect of introducing biogas to the cooking fuel mix. The ‘modern’ scenario has the lowest FEP and MEP, while the ‘independent’ scenario has the lowest TAP and MEP similar to that of the ‘modern’.

3.2.4. Ecotoxicity (FETP, METP, TETP)

In the current situation, FETP and METP are primarily due to LPG (47–49%). In the case of TETP, fuel wood and crop residues are the main contributors (32–37%). A lower aquatic ecotoxicity (FETP and METP) is expected in all future scenarios despite the higher fraction of LPG due to the credits in the biogas system. The lowest FETP and METP are seen in the ‘independent’ scenario which has the highest fraction of biogas and no LPG in the mix. A reduction in TETP is found in the BAU and ‘modern’ scenarios due to the lower share of solid biomass fuels. However, in the ‘independent’ scenario, a higher fraction of solid

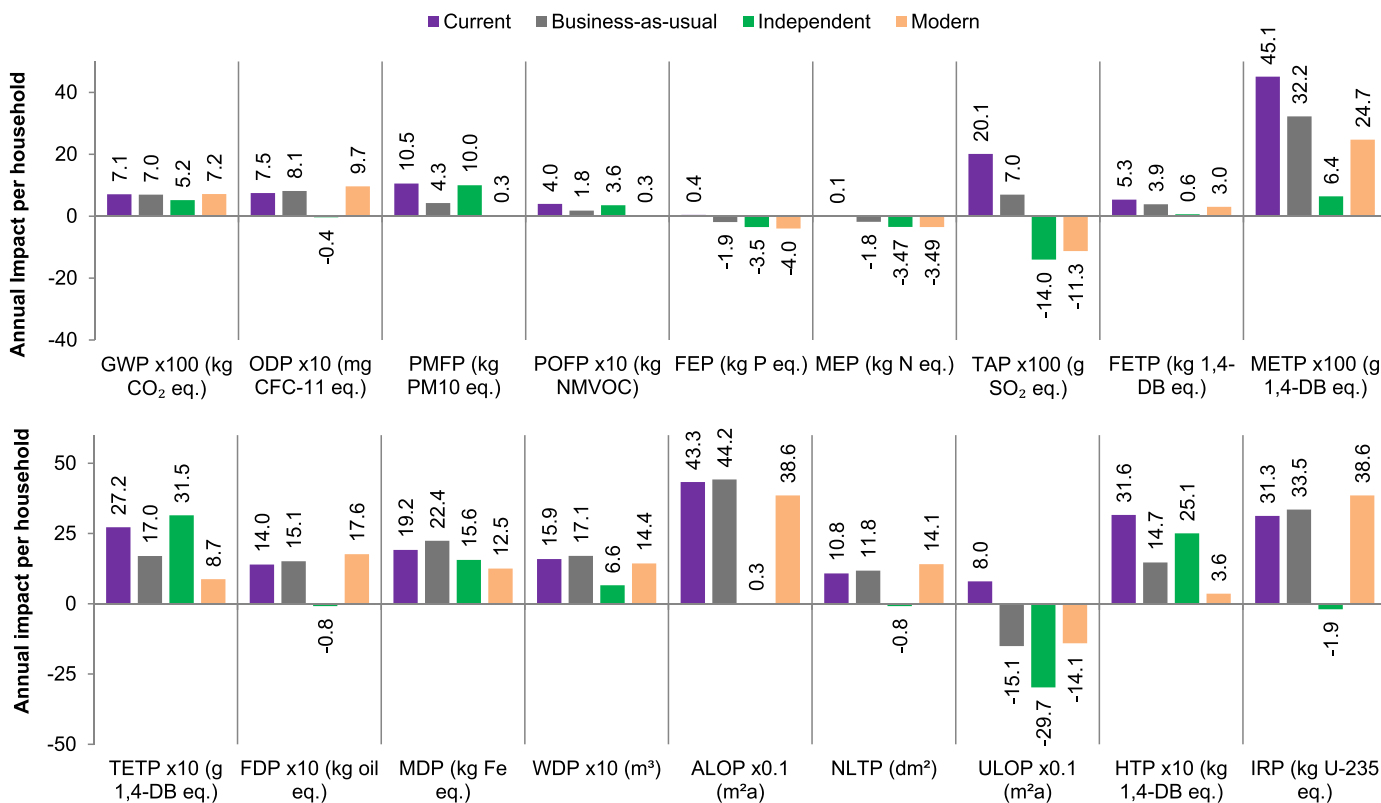


Fig. 5. Life cycle environmental impacts of current and future cooking scenarios. [Annual cooking energy demand: 5 GJ/household. Data labels are cradle-to-grave totals to be multiplied by factors on the x-axis where relevant. For impact nomenclature, see Fig. 3 and for scenario definition, see Section 2.2.3.]

biomass combined with the high TETP of biogas results in a 16% higher impact compared to the current situation. The 'modern' scenario has the lowest TETP.

3.2.5. Resource depletion (FDP, MDP, WDP)

Almost all (>89%) of the FDP and WDP in the current situation is attributed to LPG and kerosene. LPG also makes a major contribution (30%) to MDP, although wood and crop residues are also relevant contributors (31% and 23%, respectively) due to the shorter lifespan of the stove for solid fuels and its subsequent impact on resource depletion. With more LPG in the BAU and 'modern' scenarios, FDP in these cases is proportionally higher. MDP and WDP are also higher in the BAU scenario for the same reason. The 'independent' scenario has lower resource depletion as LPG and kerosene are not present in the fuel mix. Despite having a higher LPG fraction, the 'modern' scenario has lower MDP and WDP stoves as solid fuels are no longer used as well as due to the credits in the biogas system. Overall, as shown in Fig. 5, the 'independent' scenario has the lowest FDP and WDP, while the 'modern' scenario has the lowest MDP.

3.2.6. Land use (ALOP, NLTP, ULOP)

Land use impacts in the current situation are primarily attributable to LPG (66–91% of the total impacts). The BAU scenario has higher ALOP and NLTP but lower ULOP than the current situation. More widespread use of LPG explains the higher impacts, but in the case of ULOP the biogas credits are sufficient to counteract any increase. With higher biogas fractions in the 'independent' and 'modern' scenarios, land use impacts are lower. The exception is the NLTP of the 'modern' fuel mix in which higher impacts of the LPG fraction outweigh the credits for the biogas system. Among the future scenarios, the 'independent' fuel mix has the lowest impacts in all land use categories. This is attributed to the absence of LPG and

kerosene which have the highest land use requirements after diesel-derived electricity (see Section 3.1).

3.2.7. Human health (HTP, IRP)

Almost two thirds (64%) of HTP in the current fuel mix is attributed to charcoal, while LPG is the main contributor (86%) to IRP. The future scenarios have lower HTP than the current situation, with the 'modern' scenario being the best option. In contrast, only the 'independent' scenario has lower IRP compared to the current situation due to the phasing out of LPG. Less charcoal and more LPG in the BAU and 'modern' scenarios explain the trends in HTP and IRP, respectively. However, the 'independent' scenario has more charcoal in the mix, but it has lower HTP due to the improved stove efficiency and the credits in the biogas system.

3.3. Local environmental and health impacts

One of the drivers for clean cooking fuels in the SDG is to reduce the direct exposure of households to emissions from combustion of fuels during cooking (International Energy Agency, 2018b). Hence, a comparative analysis of the local impacts from the use of different fuels for cooking is also considered. These results are presented in Figs. 6–9 for both the individual fuels and their different mix in the current situation and the 2030 scenarios. As electric stoves have no emissions at the point of use they are not shown in the figures. None of the fuels contributes to ozone depletion, resource depletion, land use and ionising radiation during their use for cooking so these impacts are excluded from further analysis. For more details on the contribution of the use stage to the total impacts of different fuels, see Fig. S2 in the SI.

The next section discusses first the local impacts of the individual fuels, followed by the equivalent impacts for their supply mix in the current situation and the 2030 scenarios.

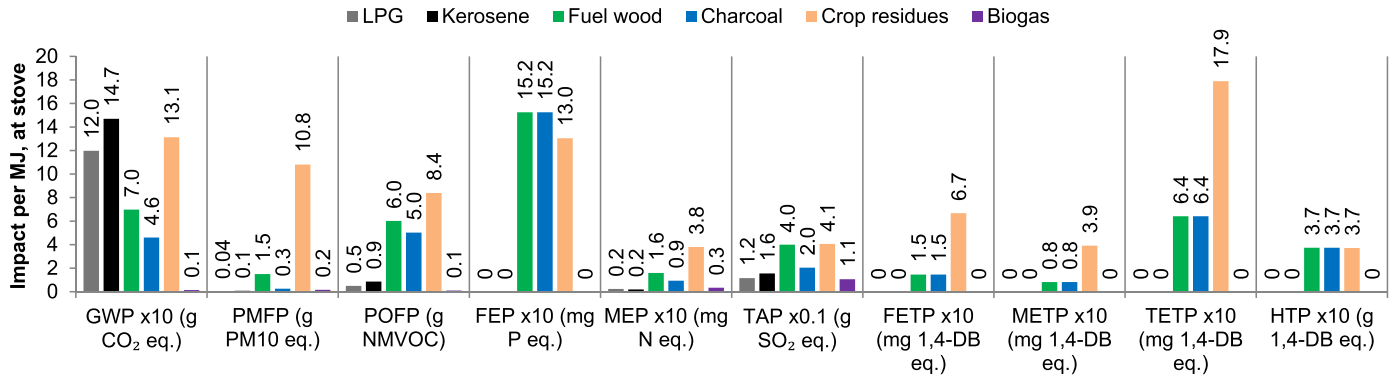


Fig. 6. Local environmental impacts of cooking fuels associated with air emissions from combustion of fuels. [Data labels are cradle-to-grave totals to be multiplied by factors on the x-axis where relevant. For impact nomenclature, see Fig. 3.]

3.3.1. Fuels

The use stage is the largest source of the life cycle GWP (>75%) for all cooking fuels, except for charcoal, which incurs high GHG emissions during the upstream carbonisation process. As can be seen in Fig. 8, kerosene has the highest direct GWP, followed closely by crop residues and LPG. As discussed in Section 3.1.1, the GWP of LPG and kerosene is mainly due to CO₂ emissions from combustion and for biomass fuels due to methane from incomplete combustion (as biogenic CO₂ is not considered).

Among the biomass options, crop residues have the highest local emissions of particulate matter (PM) and non-methane volatile organic compounds (NMVOC), contributing to PMFP and POFP, respectively. These emissions contribute to almost all (>99%) life cycle PMFP and POFP of crop residues. The same also applies to fuel wood in terms of life cycle contributions, but these two impacts are much lower for the

fuel wood than crop residues because of lower emissions of PM and NMVOC, as well as a slightly higher stove efficiency. Fuel wood and crop residues also cause the highest local TAP due to the high combustion emissions of NO_x and SO₂. For the fossil fuels, combustion accounts for only 26–33% of the life cycle TAP, but for solid biomass fuels these cause >95% of the total impact. Metal content in the residual ash is the source of local ecotoxicity and human toxicity impacts, with crop residues again having the greatest impacts in these categories. However, the local HTP of fuel wood and charcoal is comparable to that of crop residues.

A further assessment of the local health impacts of the cooking fuels is presented in Fig. 7 using the global weighted average (GLO) and regionalised endpoint indicators for PMFP and POFP in the seven SEAP regions (as explained in Section 2.3). It can be seen that human health impacts related to PMFP (Fig. 7a) are 2–4 orders of magnitude higher

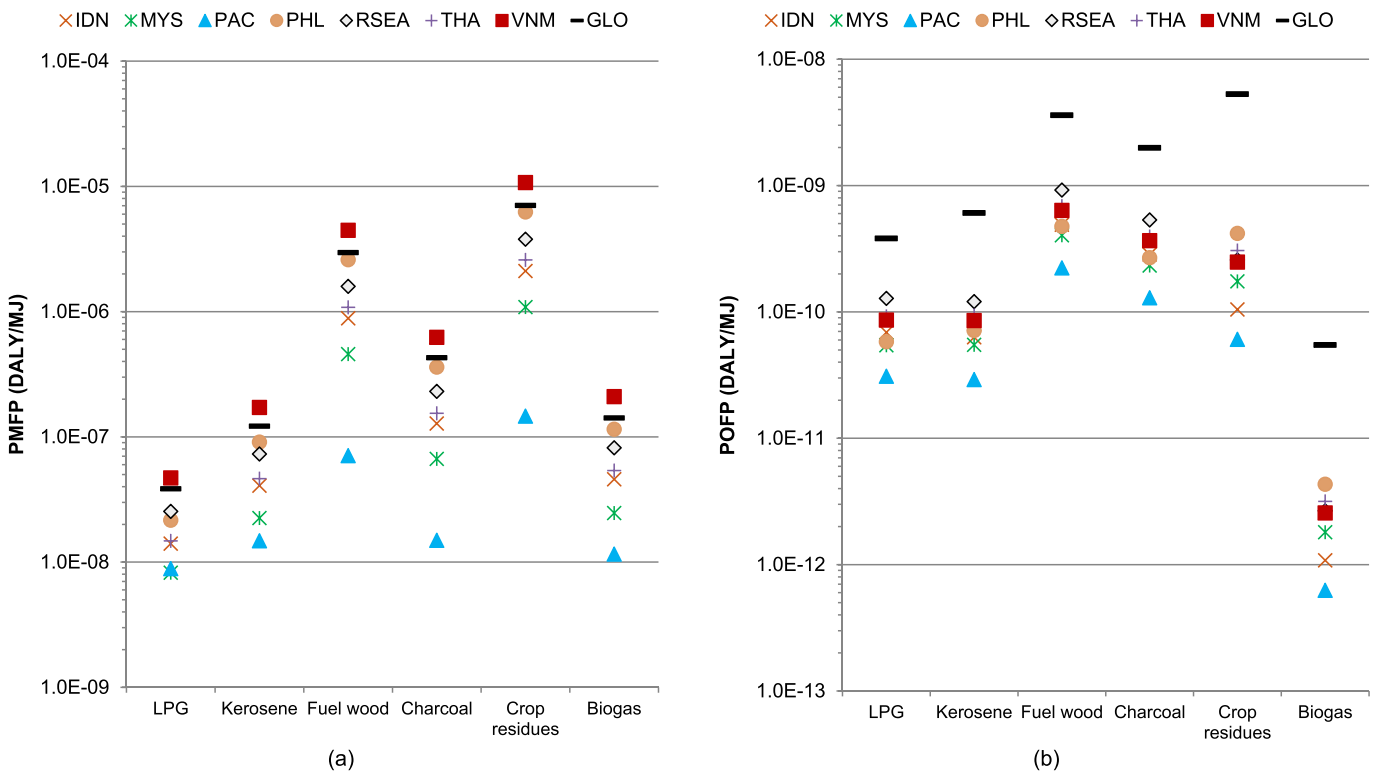


Fig. 7. Endpoint local human health impacts of cooking fuels from (a) particulate matter and (b) oxidant (ozone) formation using regionalised characterisation factors for the Southeast Asia-Pacific region in comparison with the global weighted average (GLO) impacts. [The impacts are expressed per MJ delivered at stove. GLO: global weighted average. DALY: disability-adjusted life years. For impact nomenclature, see Fig. 3 and for regions' acronyms Section 2.3.]

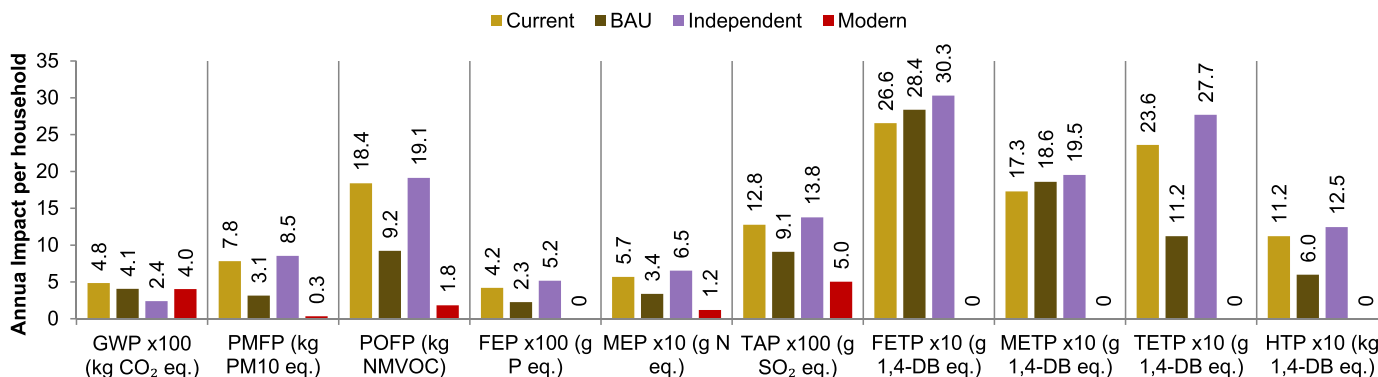


Fig. 8. Local environmental impacts of current situation and future scenarios associated with air emissions from combustion of fuels. [Annual cooking energy demand: 5 GJ/household. BAU: Business as usual. Data labels are cradle-to-grave totals to be multiplied by factors on the x-axis where relevant. For impact nomenclature, see Fig. 3 and for the definition of the current situation and scenario, see Section 2.2.3.]

than from POFP (Fig. 7b) for both the GLO and regionalised endpoint indicators. Using the latter shows similar trends to the midpoint PMFP and POFP (Fig. 6) in terms of fuel ranking: solid biomass fuels remain the worst options for both impacts, LPG is still the best fuel for PMFP and biogas has the lowest POFP for all of the SEAP regions. However, switching between the GLO and regionalised characterisation results causes a change in ranking: with the GLO characterisation, crop residues have the worst POFP, while with the regionalised indicators, fuel wood is the worst option. Nonetheless, solid biomass fuels consistently perform worse than LPG and kerosene for the local PMFP and POFP for both the GLO and regionalised impacts.

3.3.2. Current fuel mix and future scenarios

The ranking of the current situation and future scenarios for the local environmental impacts exhibits a different trend compared to the full life cycle (Fig. 5). As shown in Fig. 8, the BAU scenario has lower use-stage impacts compared to the current situation, except in aquatic ecotoxicities (FETP and METP). While the 'independent' scenario had significantly lower life cycle impacts than the others, it performs the worst in all impacts generated locally (4–23% higher than the current fuel mix), aside from GWP. This is attributed to the higher share of solid biomass fuels, resulting in higher local environmental impacts, as discussed in the previous section.

Therefore, these results highlight a stark trade-off between the local and life cycle impacts. Moreover, a second trade-off is highlighted by the 'modern' scenario: it has the highest life cycle GWP (see Fig. 5), but by far the lowest local impacts (17–100% lower than the current fuel mix; Fig. 8) as it does not have solid biomass fuels. These trade-offs should be considered carefully by policy and other decision makers to ensure that global goals, such as mitigation of climate change, are not pursued at the expense of local health and environmental impacts.

The analysis of the globally-averaged and regionalised impacts for the current situation and future scenarios reveals in Fig. 9 that PMFP is again a more significant cause of local human health impacts (by 2–3 orders of magnitude) than POFP. Independent of the regionalisation, the BAU and 'modern' scenarios have lower impacts than the current fuel mix, with the 'modern' mix having the lowest local PMFP and POFP. Depending on the region, it has 78–97% lower PMFP and 80–87% lower POFP than the current fuel mix. On the other hand, the 'independent' scenario has 23–28% higher PMFP and 11–17% higher POFP than the current situation.

It can also be noticed in Fig. 9 that the local endpoint PMFP and POFP vary across the regions, often by more than an order of magnitude. A similar trend applies for the impacts of the individual fuels (Fig. 7). These results suggest that using the globally-averaged rather than regionalised impacts results in an overestimation of the actual local PMFP and POFP in the SEAP regions. The exception to this trend is

PMFP in Vietnam which is underestimated if the GLO factors are used (see Figs. 7 and 9).

Fig. 9 also indicates that, of the seven regions assessed, the highest PMFP is estimated for Vietnam and the Philippines, while the highest POFP is found for Cambodia, Laos and Myanmar. Conversely, the lowest local PMFP and POFP are expected in the Pacific islands. Similar trends are observed when comparing individual fuel types (Fig. 7). These differences between regions are due to the background concentrations of pollutants and mortality and morbidity rates for cardio-pulmonary and respiratory diseases (van Zelm et al., 2016). Hence, it may be argued that there should be a higher impetus for a transition to clean cooking in remote communities in Vietnam, the Philippines, Cambodia, Laos and Myanmar as these regions are more vulnerable to the negative health effects of cooking.

4. Conclusions and recommendations

This paper has evaluated the environmental impacts of household cooking in remote communities, considering both the life cycle and local impacts of seven cooking fuels and their differing mixes in three 2030 scenarios. The results reveal that biogas from manure is environmentally the most sustainable cooking fuel with 16 lowest life cycle impacts out of 18 categories considered. However, fuel wood is the best option for climate change, with relatively low other impacts, apart from freshwater eutrophication. Cooking using electricity is the worst option in 13 out of 18 categories since it is typically generated from diesel in off-grid communities. LPG and kerosene have higher resource depletion and land use impacts compared to biomass fuels derived from waste. Solid biomass fuels (fuel wood, charcoal and crop residues) have high freshwater eutrophication, terrestrial ecotoxicity and human toxicity. In addition, direct emissions from their combustion cause significant local health and environmental impacts.

Compared to the current cooking fuel mix, the BAU scenario has higher impacts in seven categories, the 'independent' scenario in terrestrial ecotoxicity alone and the 'modern' scenario in five categories. Compared to the other two future scenarios, the 'independent' is the best option in 11 categories, mainly due to the use of biogas and the credits for the displacement of mineral fertilisers by the digestate. This scenario also has eight net-negative impacts.

Based on these results, and assuming equal importance of all impacts, a transition to the 'independent' cooking fuel mix is a preferred option for the life cycle impacts. An additional advantage of this scenario is energy independence. However, the local impacts, including on health, associated with the high use of solid biomass are higher in this scenario than in the others; in most cases higher than the present day. Consequently, there is a trade-off between local and global impacts

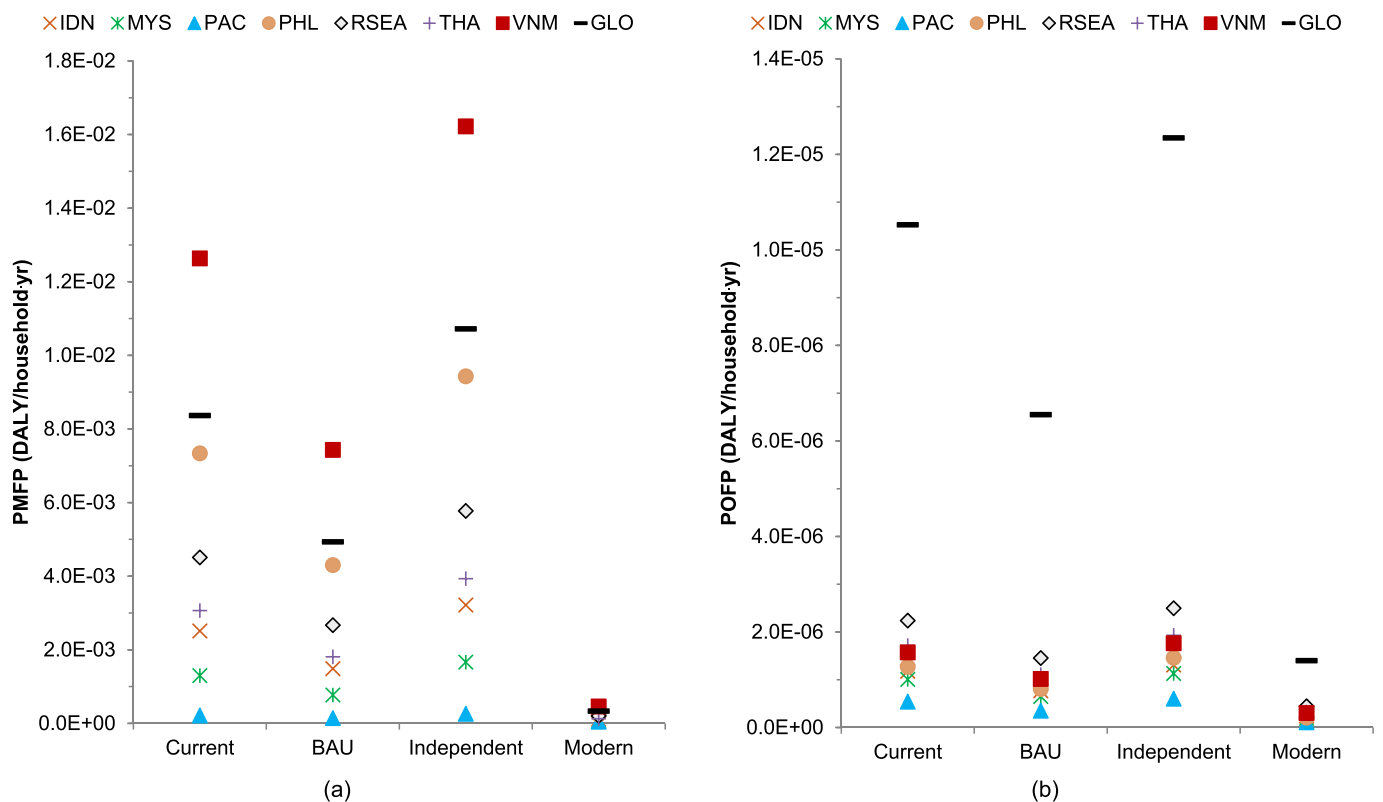


Fig. 9. Endpoint local human health impacts for the current situation and 2030 scenarios related to (a) particulate matter and (b) oxidant (ozone) formation using regionalised characterisation factors for the Southeast Asia-Pacific region in comparison with the global weighted average (GLO) impacts. [Annual cooking energy demand: 5 GJ/household. BAU: Business as usual. GLO: global weighted average. DALY: disability-adjusted life years. For impact nomenclature, see Fig. 3, for scenario definition, see Section 2.2.3 and for regions' acronyms Section 2.3.]

which should be considered carefully to avoid solving the latter at the expense of the former.

Regionalised impact assessment also reveals that local endpoint health-related impacts can vary significantly between regions, but the relative rankings between fuels and scenarios are not significantly affected. Remote communities in Vietnam and the Philippines are found to be most susceptible to health effects resulting from exposure to particulate matter, while Cambodia, Laos and Myanmar are vulnerable to oxidant (ozone) formation during cooking. If the local impacts are prioritised, the 'modern' scenario is the preferred option for remote communities in Southeast Asia-Pacific nations as it reduces the impacts by 17–100%.

Future work could consider local biomass availability and current cooking practices across the SEAP and other developing regions. Additional scenarios, especially those integrated with other energy sectors (e.g. power), could also be investigated. Furthermore, the analyses presented here do not include the economic and social dimensions of sustainability, which could be considered in future studies.

Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2019.136445>.

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