Estimated health effects from domestic use of gaseous fuels for cooking and heating in high-income, middle-income, and low-income countries: a systematic review and meta-analyses

Elisa Puzzolo, Nigel Fleeman, Federico Lorenzetti, Fernando Rubinstein, Yaojie Li, Ran Xing, Guofeng Shen, Emily Nix, Michelle Maden, Rebecca Bresnahan, Rui Duarte, Lydia Abebe, Jessica Lewis, Kendra N Williams, Heather Adahir-Rohani, Daniel Pope

Summary

Background Exposure to household air pollution from polluting domestic fuel (solid fuel and kerosene) represents a substantial global public health burden and there is an urgent need for rapid transition to clean domestic fuels. Gas for cooking and heating might possibly affect child asthma, wheezing, and respiratory health. The aim of this review was to synthesise the evidence on the health effects of gaseous fuels to inform policies for scalable clean household energy.

Methods In this systematic review and meta-analysis, we summarised the health effects from cooking or heating with gas compared with polluting fuels (eg, wood or charcoal) and clean energy (eg, electricity and solar energy). We searched PubMed, Scopus, Web of Science, MEDLINE, Cochrane Library (CENTRAL), Environment Complete, GreenFile, Google Scholar, Wanfang DATA, and CNKI for articles published between Dec 16, 2020, and Feb 6, 2021. Studies eligible for inclusion had to compare gas for cooking or heating with polluting fuels (eg, wood or charcoal) or clean energy (eg, electricity or solar energy) and present data for health outcomes in general populations. Studies that reported health outcomes that were exacerbations of existing underlying conditions were excluded. Several of our reviewers were involved in screening studies, data extraction, and quality assessment (including risk of bias) of included studies; 20% of studies were independently screened, extracted and quality assessed by another reviewer. Disagreements were reconciled through discussion with the wider review team. Included studies were appraised for quality using the Liverpool Quality Assessment Tools. Key health outcomes were grouped for meta-analysis and analysed using Cochrane's RevMan software. Primary outcomes were health effects (eg, acute lower respiratory infections) and secondary outcomes were health symptoms (eg, respiratory symptoms such as wheeze, cough, or breathlessness). This study is registered with PROSPERO, CRD42021227092.

Findings 116 studies were included in the meta-analysis (two [2%] randomised controlled trials, 13 [11%] case-control studies, 23 [20%] cohort studies, and 78 [67%] cross-sectional studies), contributing 215 effect estimates for five grouped health outcomes. Compared with polluting fuels, use of gas significantly lowered the risk of pneumonia (OR 0·54, 95% CI 0·38–0·77; p=0·00080), wheeze (OR 0·42, 0·30–0·59; p<0·0001), cough (OR 0·44, 0·32–0·62; p<0·0001), breathlessness (OR 0·40, 0·21–0·76; p=0·0052), chronic obstructive pulmonary disease (OR 0·37, 0·23–0·60; p<0·0001), bronchitis (OR 0·60, 0·43–0·82; p=0·0015), pulmonary function deficit (OR 0·27, 0·17–0·44; p<0·0001), severe respiratory illness or death (OR 0·27, 0·11–0·63; p=0·0024), preterm birth (OR 0·66, 0·45–0·97; p=0·033), and low birth weight (OR 0·70, 0·53–0·93; p=0·015). Non-statistically significant effects were observed for asthma in children (OR 1·04, 0·70–1·55; p=0·84), asthma in adults (OR 0·65, 0·43–1·00; p=0·052), and small for gestational age (OR 1·04, 0·89–1·21; p=0·62). Compared with electricity, use of gas significantly increased risk of pneumonia (OR 1·26, 1·03–1·53; p=0·025) and chronic obstructive pulmonary disease (OR 1·15, 1·06–1·25; p=0·0011), although smaller non-significant effects were observed for higher-quality studies. In addition, a small increased risk of asthma in children was not significant (OR 1·09, 0·99–1·19; p=0·071) and no significant associations were found for adult asthma, wheeze, cough, and breathlessness (p>0·05). A significant decreased risk of bronchitis was observed (OR 0·87, 0·81–0·93; p<0·0001).

Interpretation Switching from polluting fuels to gaseous household fuels could lower health risk and associated morbidity and mortality in resource-poor countries where reliance on polluting fuels is greatest. Although gas fuel use was associated with a slightly higher risk for some health outcomes compared with electricity, gas is an important transitional option for health in countries where access to reliable electricity supply for cooking or heating is not feasible in the near term.

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Department of Public Health, Policy, and Systems (E Puzzolo PhD, F Lorenzetti MSc, F Rubinstein MD, E Nix PhD, Prof D Pope PhD) **and Liverpool Reviews and Implementation Group,** (N Fleeman MPH, M Maden PhD, R Bresnahan PhD, R Duarte PhD), **University of Liverpool, Liverpool, UK; College of Urban and Environmental Sciences, Peking University, Beijing, China** (Y Li MSc, R Xing MSc, G Shen PhD)**; Public Health, Environmental and Social Determinants of Health, WHO, Geneva, Switzerland** (L Abebe PhD, J Lewis PhD, K N Williams PhD, H Adhair-Rohani MPH)

Correspondence to: Dr Elisa Puzzolo, Department of Public Health, Policy, and Systems, University of Liverpool, Liverpool, L69 7ZX, UK **puzzoloe@liverpool.ac.uk**

Research in context

Evidence before this study

An extensive body of evidence has demonstrated that the use of certain fuels for household energy needs (eg, biomass, coal, and kerosene) are detrimental to health, causing substantial disease burden. Natural gas (methane) is extensively used in high-income countries for cooking and heating. Liquefied petroleum gas (a mix of propane or butane stored in pressurized cylinders) is being promoted as a clean scalable cooking energy alternative in developing economies. Biogas is a mix of gases (primarily methane) derived from renewable feedstock and is mainly promoted as a cooking fuel among rural households with access to organic materials such as animal waste and agricultural residues. For this review and meta-analyses, we conducted extensive searches of PubMed, Scopus, Web of Science, MEDLINE, Cochrane Library (CENTRAL), Environment Complete, GreenFile, Google Scholar, Wanfang DATA, and CNKI. We focused on articles published between 1980 and 2021. Our search specifically targeted liquid and gaseous household fuels used for cooking or heating, comparing them to a clearly defined reference group (either polluting or clean fuel[s]), with relevance to health effects or symptoms in the general population.

Added value of this study

To our knowledge, this study is the first systematic review with meta-analyses that has comprehensively assessed the health effects of use of gaseous fuels (natural gas, liquefied petroleum gas, and biogas) for household cooking and heating on a global scale. Previous systematic reviews have looked at single health outcomes (eg, adverse pregnancy outcomes, acute lower respiratory illness such as acute lower-respiratory infections or asthma) or focused on specific energy uses (eg, only gas cooking), and have not considered both polluting (solid fuels and kerosene) and clean (electricity) reference options. By summarising both potential positive and negative health effects from household use of gaseous or alcohol fuels, this synthesis provides important contemporary evidence to inform national clean-energy policies needed to address the burden of disease from household air pollution in low-income and middle-income countries (LMICs).

Implications of all the available evidence

This study shows a lower risk for key health outcomes when switching from polluting solid fuels and kerosene to use of clean gaseous fuels for cooking or heating. Our study also identifies a modest increase in risk from use of gaseous fuels compared with electricity for a few health outcomes, including acute lower respiratory infections and chronic obstructive pulmonary disease (although not statistically significant when focusing on evidence from higher-quality studies). For LMICs reliant on polluting solid fuels and kerosene, transitions to gaseous fuels for cooking or heating can potentially produce substantial health benefits. However, where transitions to clean energy such as electricity are a realistic option (ie, scalable and accessible in the short term) further protection of health is probable.

Introduction

Exposure to household air pollution from combustion of solid fuels (eg, biomass and coal) and kerosene for household energy is among the largest global environmental public health burdens, responsible for 3·2 million preventable deaths annually.[1] Modern domestic liquid and gaseous fuels, such as liquefied petroleum gas (also known as LPG), biogas, natural gas, and alcohols (eg, ethanol) are considered clean for health in terms of emissions at point of use[2] and have the potential for scale in low-income and middle-income countries (LMICs)[3], where the burden from reliance on polluting fuels is greatest.[4] Although electricity is the cleanest household energy, with zero emissions at point of use, and is increasingly being used in high-income countries (HICs), for many LMICs access to reliable electricity is limited and it is not a realistic scalable option for cooking.

See Online for appendix

The urgent need for rapid transition to clean domestic fuels to address household air pollution-related disease burden is internationally recognised. A systematic synthesis of evidence on the health effects (both positive and negative) from domestic use of liquid and gaseous fuels is required to inform policies for scale. The evidence is time crucial because the Sustainable Development Goals (SDGs) 2030 time horizon is only a few years away, and the SDG7 clean modern energy for all is crucial to meet other SDGs, including health and wellbeing (SDG3), gender equality (SDG5), and climate action (SDG13).

This Article builds on a broader systematic review led by our group and commissioned by WHO looking at all household energy uses (including lighting).[5] This wider review comprehensively searched for studies of all health effects, symptoms, or injuries (a full list is provided in the appendix p 2) associated with the use of liquid or gaseous fuels for household energy, and emissions of health-damaging pollutants (eg, particulate matter [$PM_{2.5}$], carbon monoxide [CO], nitrogen oxides [NO_x], and polycyclic aromatic hydrocarbons). All identified studies are compiled in the WHO Health Effects of Household Liquid & Gaseous Fuels Database.[6]

The WHO database was the starting point to specifically assess the health effects of using gaseous and liquid fuels for cooking and heating (the subject of this Article). All polluting liquid fuels used for lighting (eg, kerosene, diesel, and gasoline) were excluded because of their negative health effects, which have been extensively documented.[7–9] Kerosene used for cooking was included as a reference polluting fuel in comparison with liquid and gaseous fuels. Liquid alcohol fuels were included in the scope of this systematic review, but because of a scarcity of studies identified in the published literature, these types of fuels were not included for pooling through meta-analyses.

In light of current evidence that suggests that gas for cooking and heating can potentially affect child asthma and wheezing[10–12] and other respiratory health issues[13,14] (through elevated emissions of NO_2),[15,16] this Article aims to highlight the state of evidence for these outcomes and provides more robust pooled estimates of effect.

Methods

Search strategy and selection criteria

The broader systematic review (resulting in the WHO Health Effects of Household Liquid & Gaseous Fuels Database), has been previously described.[5] This review comprised an extensive and comprehensive appraisal of published literature done by our experienced reviewers from the University of Liverpool, Liverpool, UK, and Peking University, Beijing, China. All liquid and gaseous household fuels used for cooking, heating, and lighting, related to any objective measure of exposure to pollution or health effect or symptom, were eligible for inclusion. Exposure was defined as personal exposure to air pollutants known to have detrimental effects on health (a full list is included in the appendix p 2).

We searched major international bibliographical databases from Jan 1, 1980, until the date of the searches with no language restriction. The databases we searched included MEDLINE (to Dec 16, 2020), Cochrane Library (to Dec 18, 2020), CENTRAL (to Dec 18, 2020), Environment Complete (to Dec 18, 2020), GreenFile (to Dec 18, 2020), PubMed (to Jan 5, 2021), Scopus (to Jan 5, 2021), Web of Science (to Jan 5, 2021), Google Scholar (to Jan 6, 2021), Wanfang DATA (to Feb 5, 2021), and CNKI (to Feb 6, 2021).

For the systematic review and meta-analyses presented in this Article, the WHO database was appraised by screening the listed studies to identify studies specifically focused on the health effects and symptoms from cooking and heating with liquid and gaseous fuels. For the present review, fuels that were used for lighting and studies reporting on personal exposures to specific pollutants with no associated health outcome were not included.

The abstracts of relevant studies were screened by experienced reviewers (DP, FL, EP, NF) using the following inclusion criteria: the studies had to investigate cooking, heating, or both cooking and heating, along with any gaseous or liquid (alcohol) fuel, and any health effect or symptom. Outcomes related to fuel use that did not relate to household air pollution exposure were excluded, including outcomes related to injury (eg, burns and scalds) and poisoning (eg, CO poisoning and accidental fuel ingestion). Studies of cooking and heating in populations from all countries and geographical contexts were eligible for inclusion. All comparisons of relevant gaseous and liquid fuels with another fuel alternative (either a clean fuel, such as electricity, or a polluting fuel, such as wood, charcoal, or kerosene) were eligible. In addition, studies for which the reference fuel was unclear were included for sensitivity analyses (eg, gas users *vs* non-gas users). Studies that only compared vented versus unvented gas appliances were excluded. Studies which reported health outcomes that were exacerbations of existing underlying conditions (eg, effects among patients with asthma) were excluded because they applied to participants already at risk and not the general population, which was the focus of the current Article.[17] This study is registered with PROSPERO, CRD42021227092.

Data extraction and quality appraisal

Data were extracted using a purposively designed form in Excel, extensively piloted and improved over 15 rounds of data extraction to capture all study outcomes, type of fuels, and comparators. Extracted data included article title, author and year, study type and size, country, setting, and context, fuel types, end use (cooking, heating, or both cooking and heating), population characteristics (sex and age), health outcomes and symptoms, and summary of results. Data from studies presented in several publications were extracted and reported as a single study. Several authors were involved in data extraction (NF, FR, FL, EP, DP, RX, YL, and EN). A 20% independent verification (NF, FR, EP, DP, and FL) of extracted studies was applied with disagreements reconciled through discussion with the wider review team.

Each study was appraised for quality at the same time as data extraction using the Liverpool Quality Assessment Tools (LQATs; appendix p 4), which have been extensively used in previous systematic reviews and meta-analyses.[18–21] Each LQAT is study design specific, comprising key areas of methodological quality and potential bias: selection (including randomisation for randomised controlled trials [RCTs]); response and follow-up bias; intervention and exposure measurement; outcome assessment; risk of confounding (including adjustment); and reporting of results. A quality score was assessed within each study design with a total of eight or nine methodological quality stars available for each study (eight stars for cross-sectional and case-control studies, and nine stars for cohort and intervention studies; appendix p 4).

For each study, quality was scored as a percentage according to the number of available aspects of quality met for each study design (with a different denominator for each design). 100% indicated maximum achievable methodological quality for a given study design. A cutoff score higher than 60% was used in sensitivity analyses to identifiy studies with at least moderate quality for each study design. These studies were compared to poorer-quality studies (less than or equal to 60%) to summarise the potential effect of methodological quality on pooled estimates of effect from the meta-analyses. For each health outcome no assumption was made for hierarchy of evidence (e.g. assigning higher quality to interventional studies than observational studies).

Data analysis

Key health outcomes and symptoms were grouped for meta-analyses under five health effects, which were: asthma (child and adult); acute lower respiratory infections (including pneumonia); chronic lung disease (including chronic obstructive pulmonary disease, chronic bronchitis, severe respiratory illness or death, and abnormal pulmonary function, assessed through spirometry); respiratory symptoms (including wheeze, breathlessness, with or without cough), and adverse pregnancy outcomes (low birth weight, preterm birth, and small for gestational age). For these outcomes, studies had similar homogeneous definitions of the health conditions allowing pooling. For exposure, use of any gaseous fuel (eg, liquefied petroleum gas, natural gas, or biogas) for household energy (eg, heating, cooking, or both cooking and heating) was combined for analysis.

For many other health outcomes (encompassing a wide range of conditions) information could not be pooled because of heterogeneity or scarcity of quantitative data. Studies that provided an effect estimate with variance (eg, odds ratios [ORs] or relative risks (RRs) with 95 CIs) for increased or decreased risk for key health outcomes and symptoms from use of liquid or gaseous fuels (as compared with polluting or clean fuels) were included in random-effects meta-analysis using Cochrane's RevMan version 5.4. Where effect estimates were not available, crude calculations of ORs (95% CIs) were undertaken if data (proportion of exposed or unexposed, with or without health outcomes) were available. For the meta-analyses, adjusted estimates were chosen over unadjusted estimates. Random-effects meta-analysis was adopted in the presence of any statistical heterogeneity (I^2 >10%). Funnel-plot asymmetry (as an indication of potential publication bias) was assessed visually (using funnel plots) and statistically (using Begg and Egger's tests) with Stata version 15. $p<0·05$ was considered to indicate a statistically significant result.

Forest Plots were stratified by broad age group (children *vs* adults) for asthma and by condition for chronic lung disease and adverse pregnancy outcomes. When studies provided estimates for both cooking and heating, the estimate for cooking was selected for meta-analyses (decided a priori by the review team for exposure proximity). Data from at least three studies were required for pooling through meta-analyses.

Separate meta-analyses were done to contrast the pooled effects comparing gaseous or liquid fuels to a clean (electricity) and polluting (eg, wood, charcoal, or kerosene) reference group. For studies in which the reference group could not be ascertained (eg, studies that only mentioned non-use of gas for cooking or heating), sensitivity analyses were done adding these studies (non-users of gas) to comparisons with the clean (electricity) reference group.

Role of the funding source

The WHO commissioned the review and defined its scope. WHO contributed to interpretation of the results including dissemination and obtained internal WHO approval for submission.

Results

Our broader and previously published systematic review,[5] used as the starting point for this study, screened 1103 full-text articles (from 48 130 records), of which 587 studies (published 1980–2021) were included in the WHO Health Effects of Household Liquid & Gaseous Fuels Database. For systematic review and meta-analyses subject to this Article, 12 additional studies were identified through further investigation of key literature, resulting in 599 studies for full-text screening. Of these, 216 studies met the inclusion criteria for the systematic review, with 116 studies (215 effect estimates) appropriate for the meta-analyses (figure 1).

The 116 studies (appendix pp 15–16) included in the meta-analyses comprised two (2%) RCTs, 13 (11%) case–control studies, 23 (20%) cohort studies, and 78 (67%) cross-sectional studies. Studies spanned 34 countries, with 60 (52%) studies from LMICs, 54 (47%) studies from HICs, and two studies (2%) involving several countries (LMICs and HICs). Most studies (92 [79%]) investigated cooking, with 17 (15%) assessing heating and seven (6%) assessing both heating and cooking. Type of gaseous fuel use was not specified for 70 studies (likely to be natural gas in HIC settings). Only one study investigated ethanol (related to stillbirth) and it was therefore not possible to do the meta-analyses on the health effects of liquid fuels.

We presented the main summary of all meta-analyses comparing gaseous fuels to polluting fuels (figure 2A) and gaseous fuels to electricity (figure 2B). The robustness of these analyses, including sensitivity analyses, are described in detail for each health outcome in the appendix (pp 18–44; studies investigating heating are highlighted with an asterisk in the forest plots). No evidence of publication bias (assessed through statistical funnel-plot asymmetry) was identified for the majority of analyses ($p>0·05$ for 18 [95%] with Begg tests and 15 (79%) with Egger's tests for the 19 funnel plots; appendix p 18–43). For some health outcomes, there was a paucity of homogeneous evidence for pooling through meta-analyses (eg, for specific cancers and cardiovascular diseases; appendix p 17).

Crude stratification by study quality (using LQATs) generally showed that pooled effect estimates were slightly larger (lower risk for gas *vs* polluting fuels and

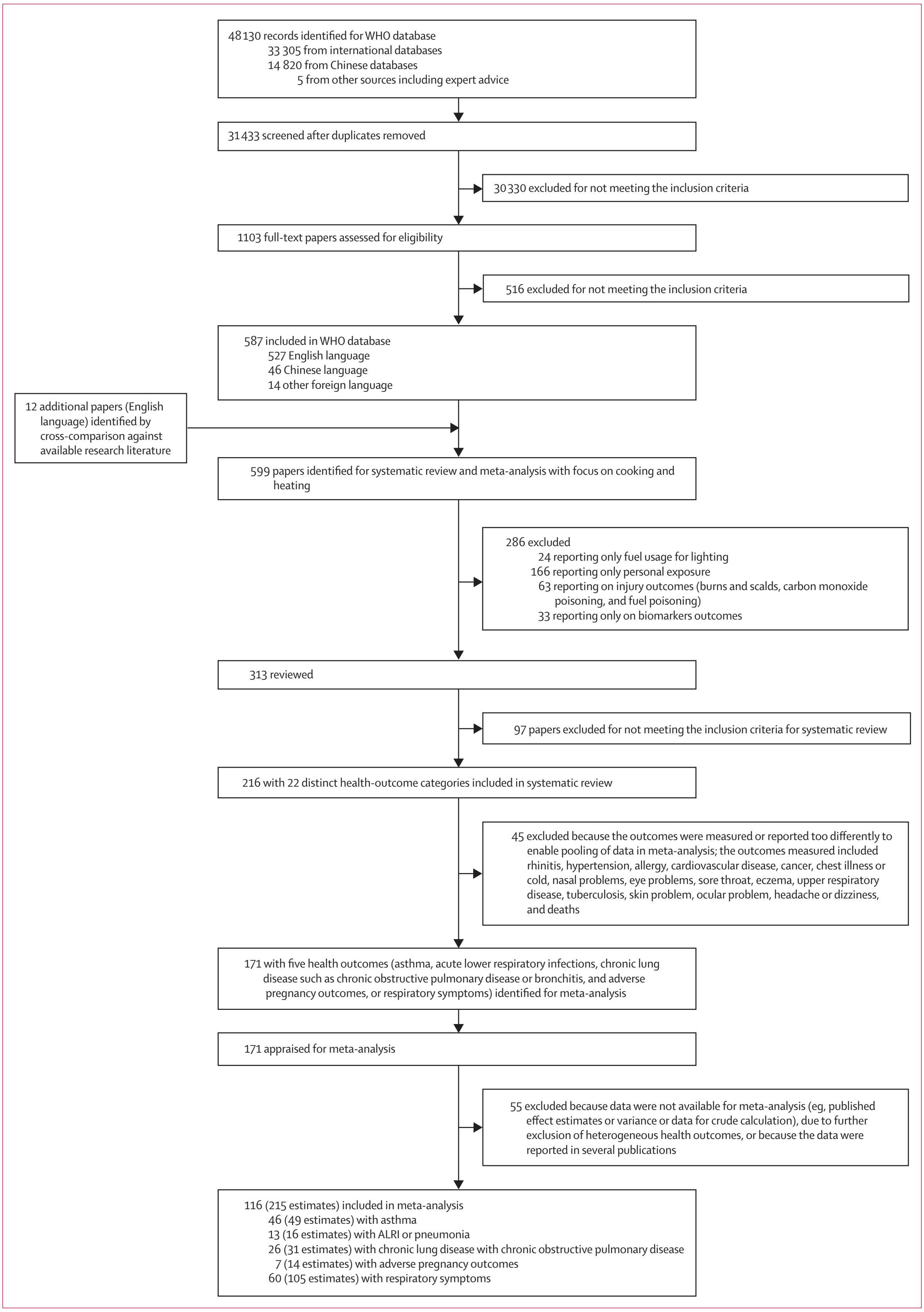


Figure 1: **Study selection flowchart**

higher risk for gas *vs* electricity) for lower-quality studies (LQAT ≤60%), including health outcomes for asthma, pneumonia, chronic lung disease, wheeze, cough, and breathlessness (appendix p 18–44).

The main results for each health outcome are described hereafter, including key sensitivity analyses that affect pooled estimates of effect. The full meta-analyses, including publication bias (funnel plots and statistical tests) and all sensitivity analyses on methodological and contextual characteristics of included studies are described in detail in the appendix (p 18–44).

46 studies (49 estimates) assessed asthma in children, adults, or both adults and children. When compared with polluting fuels (figure 3A), use of gas for cooking or heating did not appear to alter the estimate for risk of asthma in children (OR 1·04, 95% CI 0·70–1·55; p=0·84), whereas a 35% lower risk of asthma in adults was observed (OR 0·65, 0·43–1·00; p=0·052; six studies). Use of gas was found to have a larger reduction in asthma risk for studies with better adjustment for confounding than for those in which there was no adjustment for any of the key confounders (active and passive smoking, ambient air pollution [proxies], and socioeconomic status; appendix p 21).

Compared with electricity (figure 3B), using gas for cooking or heating did not result in a higher risk estimate

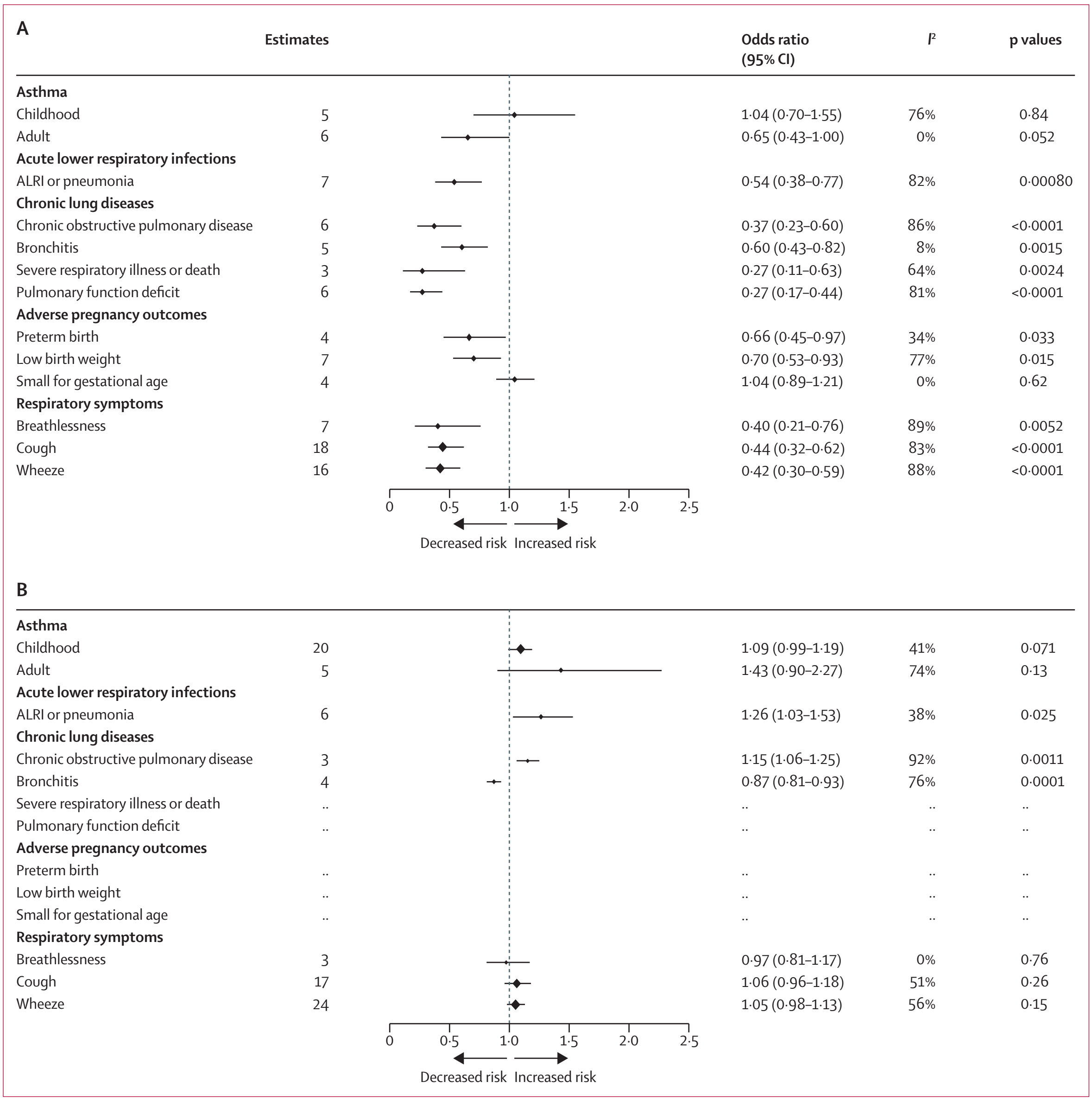
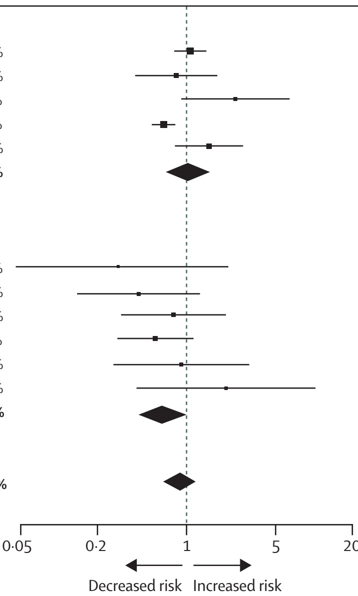


Figure 2: **Overarching summary of meta-analyses for the five health outcomes associated with use of gas for cooking or heating versus polluting fuels (A) and electricity (B)**

ALRI=acute lower respiratory infections.

A

	log(odds ratio)	Standard error	Weight	Odds ratio (95% CI)
Child asthma				
Kumar et al, 2008, LMIC*	0·0677	0·142	19·4%	1·07 (0·81–1·41)
Liu et al, 2014, LMIC	–0·1863	0·3724	9·4%	0·83 (0·40–1·72)
Nantanda et al, 2013, LMIC	0·8838	0·4935	6·5%	2·42 (0·92–6·37)
Piekarska et al, 2018, HIC*	–0·4155	0·1024	21·2%	0·66 (0·54–0·81)
vonMaffei et al, 2001, HIC*	0·4055	0·3081	11·6%	1·50 (0·82–2·74)
Subtotal (95% CI)			**68·1%**	**1·04 (0·70–1·55)**
Heterogeneity: Tau²=0·13; χ²=16·59, df=4 (p=0·0023); *I*²=76%				
Test for overall effect: Z=0·20 (p=0·84)				
Adult asthma				
Alim et al, 2014, LMIC	–1·2379	1·0107	2·0%	0·29 (0·04–2.10)
Alvis-Guzman et al, 2013, LMIC	–0·8675	0·5605	5·4%	0·42 (0·14–1·26)
Choi et al, 2015, LMIC	–0·2357	0·4773	6·8%	0·79 (0·31–2·01)
Panigrahi et al, 2018, LMIC	–0·5621	0·3448	10·3%	0·57 (0·29–1·12)
Regalado et al, 2006, LMIC	–0·0943	0·6199	4·6%	0·91 (0·27–3·07)
Zhai et al, 1995, LMIC	0·7129	0·8187	2·9%	2·04 (0·41–10·15)
Subtotal (95% CI)			**31·9%**	**0·65 (0·43–1·00)**
Heterogeneity: Tau²=0·00; χ²=3·80, df=5 (p=0·58); *I*²=0%				
Test for overall effect: Z=1·94 (p=0·052)				
Total (95% CI)			**100·0%**	**0·89 (0·67–1·19)**
Heterogeneity: Tau²=0·09; χ²=21·52, df=10 (p=0·018); *I*²=54%				
Test for overall effect: Z=0·79 (p=0·43)				
Test for subgroup differences: χ²=2·43, df=1 (p=0·12), *I*²=58·9%				



B

	log(odds ratio)	Standard error	Weight	Odds ratio (95% CI)
Child asthma				
Behrens et al, 2005, HIC	-0·2614	0·7707	0·3%	0·77 (0·17–3·49)
Casas et al, 2012, HIC	0·2852	0·2107	3·3%	1·33 (0·88–2·01)
Dekker et al, 1991, HIC*	0·2852	0·1717	4·4%	1·33 (0·95–1·86)
Diette et al, 2007, HIC	–0·1744	0·2963	1·9%	0·84 (0·47–1·50)
Dodge et al, 1982, HIC	0·3646	0·7073	0·4%	1·44 (0·36–5·76)
Garrett et al, 1998, HIC	0·5481	0·413	1·1%	1·73 (0·77–3·89)
Hölscher et al, 2000, HIC	–0·5276	0·4181	1·0%	0·59 (0·26–1·34)
Infante-Rivard et al, 1993, HIC	0·2852	0·3423	1·5%	1·33 (0·68–2·60)
Lin et al, 2013, HIC	0·0953	0·1315	6·0%	1·10 (0·85–1·42)
Liu et al, 2014, LMIC	0·3293	0·0793	8·9%	1·39 (1·19–1·62)
Lu et al, 2018, HIC*	0·0677	0·3584	1·4%	1·07 (0·53–2·16)
Moran et al, 1999, HIC	0·1398	0·1365	5·8%	1·15 (0·88–1·50)
Nakai et al, 1993, HIC	–0·4463	0·4403	0·9%	0·64 (0·27–1·52)
Norback et al, 2019, LMIC	–0·0726	0·0768	9·1%	0·93 (0·80–1·08)
Ponsonby et al, 2001, HIC*	–0·0726	0·1523	5·1%	0·93 (0·69–1·25)
Strachan et al, 1995, HIC	–0·1508	0·1752	4·3%	0·86 (0·61–1·21)
Volkmer et al, 1995, HIC	0·1398	0·0612	10·1%	1·15 (1·02–1·30)
Wang et al, 2021, LMIC	0·0198	0·1435	5·4%	1·02 (0·77–1·35)
Willers et al, 2006, HIC	0·4055	0·2606	2·4%	1·50 (0·90–2·50)
Wong et al, 2013, LMIC	–0·0305	0·0555	10·5%	0·97 (0·87–1·08)
Subtotal (95% CI)			**83·8%**	**1·09 [0·99–1·19)**
Heterogeneity: Tau²=0·01; χ²=32·05, df=19 (p=0·03); *I*²=41%				
Test for overall effect: Z=1·80 (p=0·07)				
Adult asthma				
Dai et al, 2021, HIC	0·9708	0·3938	1·2%	2·64 (1·22–5·71)
Jarvis et al, 1996 (female), HIC	0·9555	0·3945	1·2%	2·60 (1·20–5·63)
Jarvis et al, 1996, (male), HIC	–0·5447	0·4294	1·0%	0·58 (0·25–1·35)
Nkosi et al, 2015, LMIC	0·5008	0·271	2·2%	1·65 (0·97–2·81)
Smith et al, 2000, HIC	0·0392	0·0516	10·7%	1·04 (0·94–1·15)
Subtotal (95% CI)			**16·2%**	**1·43 (0·90–2·27)**
Heterogeneity: Tau²=0·18; χ²=15·19, df=4 (p=0·0043); *I*²=74%				
Test for overall effect: Z=1·50 (p=0·13)				
Total (95% CI)			**100·0%**	**1·11 (1·01–1·21)**
Heterogeneity: Tau²=0·02; χ²=47·24, df=24 (p=0·0031); *I*²=49%				
Test for overall effect: Z=2·26 (p=0·024)				
Test for subgroup differences: χ²=1·29, df=1 (p=0·26), *I*²=22·7%				

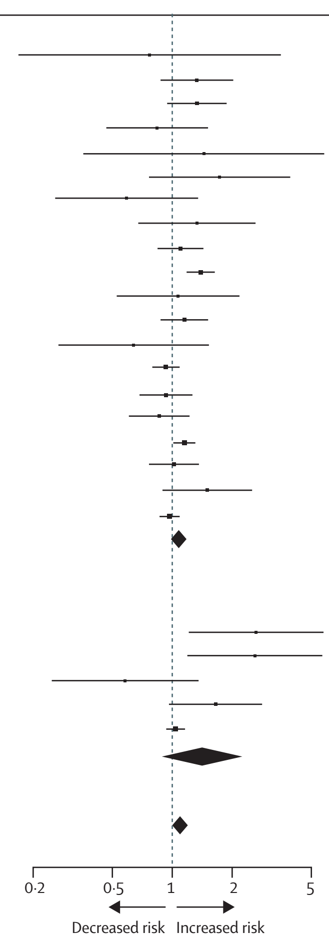


Figure 3: **Risk of Asthma in children and adults from use of gaseous fuels**
Comparison with polluting fuels (coal, biomass, or kerosene; A). Comparison with electricity (B). H=high income. LM=low and middle income. *Fuel used for heating.

for asthma in children (OR 1·09, 95% CI 0·99–1·19; p=0·071; 20 studies) nor in adults (OR 1·43, 0·90–2·27; p=0·13; five studies). Sensitivity analyses (appendix p 21), found use of gas to have a smaller, non-significant effect for studies with better adjustment for confounding than studies in which there was no adjustment for key confounders, suggesting the association between use of gas and asthma compared with electricity was at least partially explained by confounding from exposure to tobacco smoke, ambient air pollution, or socioeconomic status.

Adding studies for which the reference group could not be identified (n=13) to the comparison of gas use and electricity (appendix p 20) showed a statistically significant higher risk of asthma for gas users relative to non-users. Confounding also appeared to affect the analysis with a smaller effect for studies adjusting for key confounders than those with no adjustment for any key confounder. Stratification through sensitivity analysis by geography (HICs *vs* LMICs) and by energy use (heating *vs* cooking) did not affect the pooled effect estimates for comparisons of gas with either polluting fuels or electricity (appendix p 21).

13 studies (16 estimates) reported on acute lower respiratory infections or pneumonia. The majority (nine [69%] studies, 12 [75%] estimates) concerned children (aged 0–17 years). Almost all estimates (15 [92%]) were related to cooking (appendix p 23). Cooking with gas (relative to use of polluting fuels) significantly lowered the risk of acute lower respiratory infections or pneumonia by 46% (OR 0·54, 0·38–0·77; p=0·00080; seven studies; appendix p 23). Conversely, when compared to electricity, cooking with gas heightened the risk of acute lower respiratory infections or pneumonia by 26% (n=6: OR 1·26, 1·03–1·53; p=0·025; appendix p 23). When including non-gas users in the electricity reference group (n=9 estimates) in the sensitivity analysis (appendix p 24), a similarly higher risk was observed (22%), although it was no longer statistically significant. Sensitivity analyses by methodological quality found that higher-quality studies (LQAT >60%) showed smaller, non-statistically significant effects on the risks of acute lower respiratory infections or pneumonia for use of gaseous fuels versus polluting fuels and versus electricity.

Meta-analyses of chronic lung disease were stratified by condition as follows: chronic obstructive pulmonary disease (n=9; nine estimates); bronchitis (n=9; nine estimates); pulmonary function deficit or abnormal spirometry (n=8; eight estimates); and severe respiratory illness or death (n=3; three estimates). For all chronic lung disease conditions, a statistically significant (p<0·05) lower risk was observed when using gas for cooking or heating than when using polluting fuels (appendix p 27), ranging from a reduction of 40% for bronchitis (OR 0·60, 95% CI 0·43–0·82; p=0·0015) to 73% for pulmonary function deficit (OR 0·27, 0·17–0·44; p<0·0001) and severe respiratory illness or death (OR 0·27, 0·11–0·63; p=0·0024). For all chronic lung disease conditions pooled, a statistically significant lower risk of 64% was observed (OR 0·36, 0·27–0·48; p<0·0005).

Studies comparing use of gas to electricity for cooking or heating on chronic lung disease outcomes were scarce (n=7; seven estimates across all conditions) with substantial heterogeneity (appendix p 28). A small but statistically significant higher risk for chronic obstructive pulmonary disease (15%) was observed for cooking or heating with gas compared with electricity (n=3: OR 1·15, 1·06–1·25 p=0·0011). Conversely, a small but significantly lower risk (13%) was observed for bronchitis (n=4: OR 0·87, 0·81–0·93; p<0·0001). When non-gas users were added to the electricity reference group (appendix p 29), the overall pooled estimate across all conditions did not show a significantly higher risk of chronic lung disease from cooking with gas versus electricity. For studies including adjustment for at least one key confounder and of higher methodological quality (LQAT >60%), a significantly lower risk of chronic lung disease was observed for use of gas than use of electricity in the sensitivity analysis (appendix p 30).

For the meta-analyses for adverse pregnancy outcomes, all studies were from LMICs and compared cooking with gaseous fuels to polluting fuels (n=7; 14 estimates; appendix p 32). Statistically significant lower risks of preterm birth and low birth weight were observed when using gas for cooking for pre-term birth (OR 0·66, 95% CI 0·45–0·97; p=0·033; three studies) and for low birth weight (OR 0·70, 0·53–0·93; p=0·015; seven studies). There was no statistically significant difference in the risk of infants being small for gestational age at birth when cooking with gas relative to polluting fuels. There were not enough studies or estimates (ie, not at least three estimates) to conduct sensitivity analyses.

40 studies (40 estimates) investigated cooking or heating with gas versus polluting fuels (n=16; figure 4A) or electricity (n=24; figure 4B) and self-reported symptoms of wheeze. A statistically significant lower risk of 58% was observed for wheezing when using gas for cooking versus polluting fuels (OR 0·42, 95% CI 0·30–0·59; p<0·0001).

A slightly higher but not-statistically significant risk of wheeze was observed for use of gas versus electricity. When including non-gas users (n=10) with those using electricity in sensitivity analyses, there was no significant association with risk of wheeze from gas use (p=0·065; appendix p 36). Pooled effect estimates were not affected by focus on studies of higher methodological quality (LQAT ≥60%; sensitivity analysis appendix p 37).

32 studies (35 estimates) assessed cooking or heating with gas and self-reported cough, including 18 estimates that included a polluting reference fuel and 17 estimates that included electricity. Cooking with gas (only one study assessed heating) was associated with a significant 56% lower risk of cough when compared with polluting fuels (OR 0·44, 95% CI 0·32–0·62; p<0·0001; appendix p 38). Compared to electricity, there was no significant

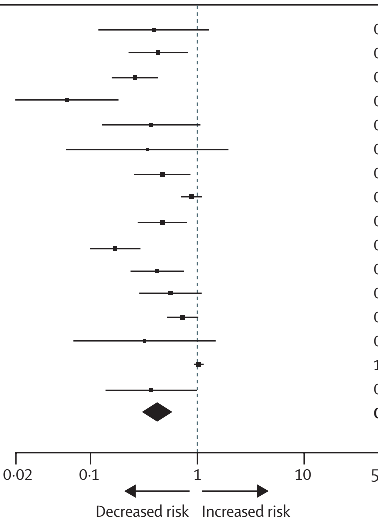
increase in risk of cough from use of gas (OR 1·06, 0·96–1·18; p=0·26; appendix p 38). Including non-users of gas (n=5) with those using electricity did not affect this result (appendix p 39). Sensitivity analyses focused on studies of higher methodological quality (LQATs >60%) showed that the main pooled-effect estimates were not affected by methodological quality (appendix pp 39–40).

Ten studies (ten estimates) assessed cooking or heating with gas and self-reported breathlessness and chest tightness. Seven studies used a polluting reference fuel and three used electricity as a reference. Cooking with gas was found to have a significantly lower risk of breathlessness than polluting fuels (OR 0·40, 0·21–0·76; p=0·0052; appendix p 42). No difference in risk of

A

	log(odds ratio)	Standard error	Weight	Odds ratio (95% CI)
Alim et al, 2014, LMIC	–0·9416	0·6014	4·2%	0·39 (0·12–1·27)
Da-Silva et al, 2012, LMIC	–0·844	0·3192	6·8%	0·43 (0·23–0·80)
Dutta et al, 2014, LMIC	–1·3471	0·2477	7·5%	0·26 (0·16–0·42)
Kouassi et al, 2012, LMIC	–2·8134	0·5605	4·5%	0·06 (0·02–0·18)
Juntarawijit et al, 2019, LMIC	–0·9943	0·5337	4·7%	0·37 (0·13–1·05)
Kaur-Sidhu et al, 2019, LMIC	–1·0788	0·885	2·6%	0·34 (0·06–1·93)
Kraii et al, 2013, LMIC	–0·755	0·3021	7·0%	0·47 (0·26–0·85)
Norbeck et al, 2019, LMIC	–0·1278	0·1095	8·7%	0·88 (0·71–1·09)
Panigrahi et al, 2018, LMIC	–0·755	0·2643	7·4%	0·47 (0·28–0·79)
Pathak et al, 2019, LMIC	–1·772	0·2707	7·3%	0·17 (0·10–0·29)
Pial et al, 2020, LMIC	–0·8675	0·2855	7·2%	0·42 (0·24–0·73)
Regalado et al, 2006, LMIC	–0·5798	0·3357	6·6%	0·56 (0·29–1·08)
Sana et al, 2019, LMIC	–0·3147	0·1634	8·3%	0·73 (0·53–1·01)
Shubhankar et al, 2016, LMIC	–1·1394	0·7754	3·1%	0·32 (0·07–1·46)
Triche et al, 2005, HIC*	0·0296	0·0467	8·9%	1·03 (0·94–1·13)
Zhai et al, 1995, LMIC	–0·9943	0·4959	5·1%	0·37 (0·14–0·98)
Total (95% CI)			**100·0%**	**0·42 (0·30–0·59)**

Heterogeneity: Tau²=0·32; χ²=129·00, df=15 (p<0·0001); I^2=88%
Test for overall effect: Z=5·09 (p<0·0001)



B

	log(odds ratio)	Standard error	Weight	Odds ratio (95% CI)
Behrens et al, 2005, HIC	0·4187	0·2507	1·7%	1·52 (0·93–2·48)
Belanger et al, 2003, HIC	0·0296	0·2843	1·4%	1·03 (0·59–1·80)
Bilderling et al, 2005, HIC	0·3853	0·1717	3·0%	1·47 (1·05–2·06)
Burr et al, 1999, HIC*	0·0953	0·0335	9·8%	1·10 (1·03–1·17)
Casas et al, 2012, HIC	0·0862	0·184	2·8%	1·09 (0·76–1·56)
Comstock et al, 2008, HIC	0·0488	0·1717	3·0%	1·05 (0·75–1·47)
Dodge et al, 1982, HIC	0·2151	0·2774	1·4%	1·24 (0·72–2·14)
Espluges et al, 2013, HIC	–0·0943	0·1195	4·8%	0·91 (0·72–1·15)
Hersoug et al, 2010, HIC	0·0488	0·1925	2·6%	1·05 (0·72–1·53)
Hosein et al, 1989, HIC	–0·3147	0·1634	3·3%	0·73 (0·53–1·01)
Jarvis et al, 1998-mixed	0·0392	0·0852	6·6%	1·04 (0·88–1·23)
Liu et al, 2014, LMIC	–0·1165	0·0608	8·1%	0·89 (0·79–1·00)
Melia et al, 1988, HIC	0·239	0·1323	4·3%	1·27 (0·98–1·65)
Nakai et al, 1993, HIC	–0·3285	0·5397	0·4%	0·72 (0·25–2·07)
Nkosi et al, 2015, LMIC	–0·5621	0·2488	1·7%	0·57 (0·35–0·93)
Ponsonby et al, 2001, HIC*	–0·0305	0·1965	2·5%	0·97 (0·66–1·43)
Samet et al, 1993, HIC	–0·1744	0·1387	4·1%	0·84 (0·64–1·10)
Shirinde et al, 2014, HIC*	0·3853	0·1253	4·6%	1·47 (1·15–1·88)
Volkmer et al, 1995, HIC	0·1484	0·0706	7·5%	1·16 (1·01–1·33)
Ware et al, 1984, HIC	0·0953	0·0695	7·6%	1·10 (0·96–1·26)
Willers et al, 2006, HIC	–0·0101	0·1485	3·7%	0·99 (0·74–1·32)
Wong et al, 2004, LMIC	0·7419	0·3941	0·8%	2·10 (0·97–4·55)
Wong et al, 2013, LMIC	–0·0408	0·0386	9·5%	0·96 (0·89–1·04)
Zacharasiewicz et al, 1999, HIC	0·1484	0·1183	4·9%	1·16 (0·92–1·46)
Total (95% CI)			**100·0%**	**1·05 (0·98–1·13)**

Heterogeneity: Tau²=0·01; χ²=52·31, df=23 (p=0·0005); I^2=56%
Test for overall effect: Z=1·44 (p=0·15)

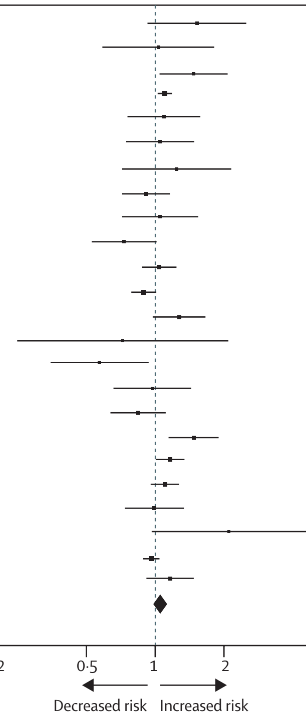


Figure 4: **Risk of wheeze in children and adults from use of gaseous fuels**
Comparison to polluting fuels (coal, biomass, or kerosene; A). Comparison to electricity (B). H=high income. LM=low and middle income. *Fuel used for heating.

breathlessness was observed from use of gas versus electricity (OR 0·97, 0·81–1·17; p=0·76; appendix p 42). When non-users of gas (n=3) were added to those using electricity, no statistically higher risk was observed from use of gas (OR 1·08, 0·97–1·21; p=0·16; appendix pp 43–44).

Discussion

This comprehensive synthesis of the effects from gaseous fuels used for cooking, heating, or both cooking and heating on key health outcomes provides a valuable evidence base for health-related policies affiliated with the clean-cooking agenda in LMICs. The meta-analyses confirm the potential health gains that can be achieved from switching from polluting solid fuels and kerosene to clean gaseous fuels in terms of reduced emissions of $PM_{2.5}$ and CO (tier 5 for International Organization for Standardization 19867-3 Voluntary Performance Targets).[22] By investigating the potential health effects of gas use for cooking or heating compared with electricity, this analysis also provides evidence to inform emerging concerns over the potential effects of cooking with gas on asthma that are shaping current energy policy in the USA[23] and Europe.[24]

Our meta-analyses indicate that cooking or heating with gas substantially (and significantly) lowers the risk of acute lower respiratory infections or pneumonia, low birth weight, preterm birth, chronic lung disease, and respiratory symptoms (including wheeze, which is closely correlated with the occurrence of asthma) relative to use of polluting fuels, such as wood, charcoal, and kerosene, which are relied on by much of the developing world. Reductions in risk for child and adult asthma were not statically significant.

Comparing cooking or heating with gas versus cooking or heating with electricity (a source of energy with zero emissions at point of use) resulted in mixed findings. For the small number of studies investigating acute and chronic respiratory outcomes, a significant increase in risk was observed for acute lower respiratory infections or pneumonia and chronic obstructive pulmonary disease with use of gas, whereas use of gas lowered the risk of bronchitis versus electricity. Although it was not possible to account for potential methodological characteristics of included studies that might explain these unexpected results for each chronic lung disease outcome, it is clear that confounding and lower methodological quality for all chronic lung disease outcomes combined affected interpretations of risk. Studies with adjustment for key confounders with or without higher methodological quality (LQATs >60%) found a lower risk of chronic lung disease from gas use than electricity, whereas those without adjustment and of lower quality found an increase in risk.

For asthma, no significant increase in risk for children and adults was found for use of gas compared with electricity. When including studies for which the reference group was unclear (ie, non-users of gas) in the sensitivity analysis, risk of childhood asthma slightly increased to 13%, reaching statistical significance. These results provide an important update (additional 27 studies, with 13 studies published since 2013) to the only other meta-analysis of cooking with gas and asthma (which compared gas users to non-users), conducted by Lin and colleagues.[10] The authors reported a 32% increased risk for current and lifetime asthma (OR 1·32, 95% CI 1·18–1·48) on the basis of 19 studies and noted that potential confounding could have exaggerated effects. To investigate the role of confounding in our meta-analyses, sensitivity analyses were done adjusting for key confounders (including active and passive smoking, ambient air pollution (proxies), and socioeconomic status; appendix p 21). We confirmed that that risk of asthma from gas use was potentially exaggerated in studies with no or limited adjustment for confounders versus those with adjustment for at least one key confounder. In addition, our analysis found no significant increase in risk of wheeze (similar in manifestation to asthma) for gas compared with electricity. Calculations of excess population-attributable risk for childhood asthma from use of gas for cooking compared with electricity or non-use[23] on the basis of older meta-analyses such as Lin and colleagues[10] (OR 1·32; 95% CI 1·18–1·48) are therefore likely to overestimate the true burden by 72% (OR 1·09 for all studies) or 85% (OR 1·05 for adjusted studies). Although asthma carries a substantial global disease burden with an estimated 455 000 global annual deaths,[25] this mortality is less than seven times the global disease burden caused by exposure to particulate matter ($PM_{2.5}$) associated with domestic use of solid fuels or kerosene for cooking. This finding is important when considering effective policies for rapid scalability of clean cooking to address the public health burden from household air pollution in LMICs.[26]

Our meta-analyses indicating the potential protective effect of gas for cooking in LMICs compared with polluting fuels for adverse pregnancy outcomes and low birth weight are not consistent with a recent finding from the largest RCT of an exclusive liquefied petroleum gas cooking intervention in four LMICs countries.[27] The Household Air Pollution Intervention Network (HAPIN) trial (published in 2022)[27] identified no difference in low birth weight for infants born in homes using liquefied petroleum gas (intervention n=1593, mean 2921 g [SD 474·3]) compared with those using solid fuels (control n=1607, mean 2898 g [467·9]). One possible explanation for the absence of effect postulated by the authors was the potential negative effect of pollution exposure during the first trimester of pregnancy that was not averted by the HAPIN trial (intervention implementation was during the second trimester).

Our meta-analyses are based on a comprehensive appraisal of international bibliographic databases (including Chinese literature) summarising the current state of the evidence including all study designs. A notable limitation is the reliance on data from observational studies, particularly cross-sectional studies, with a dearth of studies involving an RCT design. There were no RCTs for several outcomes including asthma, chronic lung disease (chronic obstructive pulmonary disease, bronchitis, and severe respiratory illness or pulmonary function deficit), wheeze, and cough or breathlessness. One RCT was identified that looked at both acute lower respiratory illness in children and adverse pregnancy outcomes (the GRAPHS trial),[28] for both acute lower respiratory infections (risk ratio 0·98, 95% CI 0·58–1·70; p=0·52) and adverse pregnancy outcomes, including low birth weight (RR 1·02, 0·72–1·45; p=0·90), preterm birth (RR 0·94, 0·51–1·71; p=0·83), and small for gestational age (RR 1·07, 0·81–1·42; p=0·61); no effect was observed contrasting the liquefied petroleum gas cookstove intervention to traditional use of biomass fuel. The authors did a rigorous assessment of exposure to $PM_{2.5}$ during the trial and noted that anticipated exposure reductions caused by cleaner cooking with liquefied petroleum gas were not observed, possibly explained by community contamination (the design was not cluster randomised and intervention households were located next to those continuing to use polluting biomass). The study also recruited women in the third trimester of pregnancy and, as discussed for the HAPIN trial,[27] therefore did not assess potential reductions in exposure across the pregnancy, including the first trimester, which might be a particularly vulnerable period. Adding the observational studies to these outcomes in our meta-analyses, showed significant intervention effects for liquefied petroleum gas with a lower risk of acute lower respiratory infections, low birth weight, and preterm birth, but not for small for gestational age.

Even with the potential misclassification of exposure[28] and health outcome,[27,28] which is likely to have resulted in more conservative estimates of effect, RCTs provide better evidence to judge causality of relationships between clean cooking interventions and health outcomes because of the reduced likelihood for confounding and bias. In studies of clean cooking interventions and positive health effects through reductions in exposure to household air pollution, accounting for potential confounding from ambient air pollution and environmental tobacco smoke will be crucial in interpreting estimates of association (in addition to other factors that influence the probable use of clean modern energy and health, such as socio-economic status). Unfortunately, as described previously, only a minority of the observational studies in the review adequately adjusted for these key confounders.

Clearly, more rigorous RCTs are required to confirm the potential intervention effects for health from transitioning from polluting biomass to liquefied petroleum gas for cooking and heating (and also the potential health gains from switching from liquefied petroleum gas to electricity). Carefully conducted RCTs will give more confidence in understanding effects from these interventions. However, for settings where populations rely on biomass and kerosene for their household energy, such trials are extremely challenging in terms of both practicality and cost (both the GRAPHS[28] and HAPIN[27] trials had to provide an unlimited supply of liquefied petroleum gas during the conduct of the trials to ensure adherence to the interventions). In the absence of this intervention-based evidence, information from the large number of observational studies can give an indication of the potential health gain that can be achieved from transitioning to clean cooking, especially if estimates of effect are consistent across different countries or contexts, and there are heterogeneous study designs in which adjustment for key confounders has been undertaken.[29]

One helpful addition to understanding the relationship between adoption of cleaner cooking fuels (eg, gas) and energy (electricity) and positive effects on health is the objective measurement of actual exposure to health-damaging pollutants (eg, respirable $PM_{2.5}$, CO, and NO_2). Such measurement can help understand potential mechanistic pathways between domestic use of gas for both potentially positive (reduced $PM_{2.5}$ and CO) and negative (eg, increased NO_2) health effects. For example, domestic use of gas has been related to raised emissions of NO_2 (potentially confounded by outdoor and traffic pollution), higher than the recently reduced WHO guideline concentration for NO_2.[30,31] Historically, few studies have attempted to objectively measure exposure to specific air pollutants; however, with the increased availability of low-cost air-quality monitors, future studies of clean cooking fuels and energy and health should incorporate such exposure measurement to strengthen interpretation of any estimates of effect. In addition, efforts should be undertaken to provide more granular evidence on factors that could influence exposure to emissions (eg, presence of gas ventilation such as through hoods), which could influence pollutant concentrations and resulting health effects.[32]

Although we focused on health outcomes that can be grouped with broadly homogeneous definitions, another potential limitation of our comprehensive synthesis of the mostly, observational evidence is the pooling of effect estimates from heterogeneous epidemiological studies with varying methods (and methodological quality), conducted across a wide range of contexts. Although we have not made assumptions on hierarchy of evidence by study design, we have attempted to account for heterogeneity using transparent meta-analytic procedures (including statistically, such as calculation of the I^2 statistic), and through interrogation of how heterogeneity effect pooled estimates (eg, through sensitivity analyses, including adjustment for confounding and study methodological quality). Of note, our crude stratification by study quality tended to show a slightly exaggerated effect for studies of lower methodological quality (≤60% LQATs) in both directions when comparing gas to polluting fuels and electricity, although this finding did not change interpretation of the associations.

In conclusion, this Article demonstrates a significantly lower risk for key health outcomes when switching from polluting solid fuels or kerosene to gaseous fuels for cooking or heating, suggesting cleaner fuels could contribute to reducing the global disease burden from exposure to household air pollution (figure 2). This potential health gain is important when designing strategies to scale the adoption of clean cooking fuels and technologies in LMICs, where the disease burden from reliance on polluting fuels is greatest. In most of these contexts, gas (particularly liquefied petroleum gas) represents the best option for effective scalability in the short-to-medium term.[33] However, given that our review has identified a small or modest increase in risk from use of gas compared with electricity for acute lower respiratory infections or pneumonia and chronic obstructive pulmonary disease (albeit from studies with methodological limitations), electricity might ultimately be the priority option for clean cooking when possible to effectively scale for exclusive use. Although further understanding the relationship between exposure to NO_2 and other pollutants emitted from gas combustion is necessary, our evidence suggests that gaseous fuels can be considered an important transitional clean fuel option in contexts without access to renewably-sourced electric cooking and heating.

Contributors

DP, EP, EN, HA-R, LA, and JL designed the study. EP, DP, GS, JL, KNW, and HA-R coordinated and supervised the study. MM, NF, EN, EP, and DP designed the literature searches. MM and NF ran the searches in the English and international (except Chinese) databases. YL and RX ran the searches in the Chinese databases. NF, DP, EP, EN, RD, RB, YL, and RX screened titles, abstracts, and full records of publications. FR, FL, NF, EP, DP, RB, RD, YL, RX, and EN extracted data and assessed risk of bias. DP, FL, NF, and EP had full access to the data in the study. DP and FL did the statistical analyses and verified the data. EP, DP, and NF wrote the manuscript. All authors critically revised the manuscript and accepted responsibility to submit for publication.

Declaration of interests

We declare no competing interests.

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Data sharing

Data sharing is not applicable to this Article because no datasets were generated or analysed during the current study. All data analysed during this study were extracted by published sources listed and fully referenced in the appendix (p 45).

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