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Metabolic energy cost of workers in agriculture, construction, manufacturing, tourism, and transportation industries

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ABSTRACT

The assessment of energy cost (EC) at the workplace remains a key topic in occupational health due to the ever-increasing prevalence of work-related issues. This review provides a detailed list of EC estimations in jobs/tasks included in tourism, agriculture, construction, manufacturing, and transportation industries. A total of 61 studies evaluated the EC of 1667 workers while performing a large number of tasks related to each one of the aforementioned five industries. Agriculture includes the most energy-demanding jobs (males: 6.0±2.5 kcal/min; females: 2.9±1.0 kcal/min). Jobs in the construction industry were the 2^{nd} most demanding (males: 4.9±1.6 kcal/min; no data for females). The industry with the 3^{rd} highest EC estimate was manufacturing (males: 3.8±1.1 kcal/min; females: 3.0±1.3 kcal/min). Transportation presented relatively moderate EC estimates (males: 3.1±1.0 kcal/min; no data for females). Tourism jobs demonstrated the lowest EC values (2.5±0.9 kcal/min for males and females). It is hoped that this information will aid the development of future instruments and guidelines aiming to protect workers' health, safety, and productivity. Future research should provide updated EC estimates within a wide spectrum of occupational settings taking into account the sex, age, and physiological characteristics of the workers as well as the individual characteristics of each workplace.

Keywords: energy expenditure, work intensity, physical activity, workload, metabolic rate, labour, industry.

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INTRODUCTION

Energy cost (EC) of work is an important aspect of occupational health and exercise physiology. Initial studies on EC primarily aimed to generate guidelines for caloric/dietary needs[1] or to determine the upper tolerance limits for daily energy expenditure during the working hours[2]. Today, the assessment of EC remains a key topic in occupational health due to the ever-increasing prevalence of work-related issues including fatigue[3], anxiety, and burn-out syndrome[4] as well as the realization that metabolic heat can lead to significant health and productivity decrements[5]. It is not surprising, therefore, that current occupational guidelines highlight the importance of EC assessment during work for the workers' health and safety, for prevention of physical and mental illness, as well as for the development of corrective action plans[6, 7].

Information about the EC is even more important when the worker is wearing protective clothing, which inhibits the body's ability to dissipate heat and may increase the EC for an activity, and/or when he/she is working in a hot environment[5, 8]. This is because the EC directly determines the heat generation in the body which needs to be dissipated to avoid excessive heat strain. For example, the Predicted Heat Strain model developed in the International Organization for Standarization (ISO) 7933 suggests that an individual [height :184 cm; weight: 84 kg; wearing typical work uniform with long sleeves (0.6 clo)] working for 8 hours indoors (air velocity: 0.3 m/sec) with a hand tool (light polishing; i.e., EC of 207 W/m^2 in a thermoneutral environment (26°C air and radiant temperatures; 40% relative humidity) is not estimated to reach a rectal temperature beyond 37.24°C and should consume ~1.5 L of fluid to remain hydrated (Figure 1). In contrast, the same individual performing heavier work with a hand tool (e.g., drilling; i.e., EC of 476 W/m^2) in the same environment while wearing the same uniform is estimated to reach a rectal temperature beyond 37.76°C and should consume ~3.9 L of fluid to remain hydrated (Figure 1).

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The importance of EC assessment is becoming increasingly pertinent due to the occurring climate change[8]. In this light, occupational health and safety recommendations and standards have been developed providing scale limits based on both environmental and metabolic data[9, 10]. For instance, the ISO has facilitated international coordination and unification of industrial standards[6] to predict the physiological strain from a stressful environment condition. The additional application of ISO standards (such as ISO 7243) provides Wet-bulb Globe Temperature (WBGT) reference values for a variety of environmental and physiological conditions (i.e. clothing and workload)[11]. Given the above, it is not surprising that the EC is a necessary component in health and safety calculations/assessments according to guidelines aiming to preserve workers' health and wellbeing[5, 6].

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While a lot of data on EC[9] for different work activities have been collected and summarized in key publications[12] in the last century[13], given the changing work content those values for EC may not all be representative anymore for today's situation. A number of studies in the literature that are most recent have assessed the EC for jobs/tasks included in industries such as (i) tourism (i.e., accommodation and food services), (ii) agriculture, (iii) construction, (iv) manufacturing, and (v) transportation. However, these studies are scattered across a multitude of scientific journals and are very difficult to locate, especially by health and safety experts working in the industry who do not always have access to specialized journals. Ainsworth et al., 2011[14] have developed a classification system of energy cost of several physical activities including activities of daily living or self-care, leisure and recreation, occupation and rest. While this compendium of activities provides information based on published lists and selected unpublished data, the values of some activities were derived from laboratory studies and not actual measurements on workers during their work shift. Moreover, this compendium does not completely cover the aforementioned five industries which are important because they have a major impact in the global economy. For instance, together they represent 40% of the European

Union's GDP and 50% of its workforce[15]. In this light, our aim in this study was to review the existing literature and provide an up-to-date detailed list of EC estimations in jobs included in (i) tourism, (ii) agriculture, (iii) construction, (iv) manufacturing, and (v) transportation.

METHODS

To identify relevant jobs across the five selected industries, we used the statistical classification of economic activities in the European Community (NACE; *Nomenclature statistique des activités économiques dans l Communauté européenne*; Rev. 2 (2008)[16]. We made every effort to conduct a systematic search, yet this was not possible since this method did not ensure that all the relevant jobs/tasks included in the 35 different NACE codes would be identified. Initial systematic searches resulted in a very small number of retrieved articles, most of which were not addressing our research question. In this light, two investigators (K.P. and A.D.F.) independently searched the PubMed and Google Scholar databases as well as the Google search engine for studies using the following keywords: "energy cost", "energy expenditure", "metabolic rate", "oxygen consumption", "heart rate", "work intensity", and "workload" in combination with job/task descriptions in the relevant NACE codes [agriculture, construction of buildings, food manufacturing, land transport, tourism (i.e., accommodation and food service), etc.]. Other than scientific rigor and quality (i.e., usage of reproducible and evidence-based methodologies), no limits were set regarding the publication type to ensure that all available information would be assessed. Thus, our search included books, research articles, reviews, reports, and conference proceedings. The retrieved list of the identified articles, reports, and books was screened by two investigators (K.P. and A.D.F.) to identify publications that were relevant to the topic under review.

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For each NACE code across the five selected industries, an estimated EC is provided via meta-analysis by averaging the data reported in the relevant studies. In cases where the EC for a job was not found during our literature search, we used the EC of an activity that was closely related or similar in type and intensity. It is important to note that the EC estimates provided by many studies are based on a significant number of workers but, for some NACE codes (e.g. some jobs within agriculture), the EC data are derived from a single study and/or from very few workers. To address this issue, the estimated EC for each NACE code was weighed based on the number of workers assessed in each study (as a function of the total number of workers assessed in all studies of that NACE code). Details about the estimation of EC for each NACE code is provided below.

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The EC was expressed in kcal/min (when reported in kJ/min, PAR, kcal/shift, etc.) to allow for comparisons within and between industries, as well as in W to harmonize with the national and international standards of ergonomic assessment[6]. Specifically, when EC values were expressed in kJ/min, the data were converted into kcal/min either using the power conversion formula $P_{[kcal/min]} = 0.239 \times P_{[kJ/min]}$. In cases where EC was expressed as “metabolic equivalent” units[14], the data were converted to kcal/min using the definition of “metabolic equivalent” as the ratio of work metabolic rate to a standard resting metabolic rate of 1.0 kcal/kg/h. When heart rate was monitored as an indicator of EC, the data were converted to kcal/min using the previously-published equation[17]: EC = gender × (-55.0969 + 0.6309 × heart rate + 0.1988 × weight + 0.2017 × age) + (1 – gender) × (-20.4022 + 0.4472 × heart rate – 0.1263 × weight + 0.074 × age), where gender is equal to 1 for males and 0 for females. When EC was given in kcal/shift, the values were divided by 3.600 minutes to convert into kcal/min. Finally, kcal/min was converted into W using the formula 1kcal/min = 69.78 W.

RESULTS

Searching procedure results

A total of 61 studies were identified as relevant during the search and were considered for subsequent analysis. Of these, 33(54%) were identified via PubMed, 23(38%) were identified via Google Scholar, while 5 (8%) were identified via the Google search engine.

Characteristics of the included studies and qualitative synthesis

The 61 studies included in the analysis were published from 1909 to 2017 (the majority being published in the period 1946-1976; Figure 2) and included 1667 workers who were evaluated while performing a large number of tasks (tourism: 4 tasks; agriculture: 137 tasks; construction: 15 tasks; manufacturing: 148 tasks; transportation: 21 tasks) related to each one of the five selected industries. The job types, number and sex of workers assessed, as well as the EC assessment method in these 61 studies across the five industries are presented in chronological order in Table 1.

In the vast majority (79%) of the studies, indirect calorimetry was employed as an assessment method of workers' EC, while in 16% and 5% of the studies heart rate monitoring and time motion analysis methods were used, respectively. Indirect calorimetry implies that the worker's oxygen consumption was measured directly (EC to be calculated from this) using either collection of expired air in Douglas bags[18)] for later analysis or using portable gas analysis systems[19)] to determine oxygen uptake (and in some cases also CO2 production). Heart rate monitoring requires measurement of heart rate (HR)[20)] during the activity, and a separate 'calibration' of the worker's individual relation between HR and oxygen uptake to then deduct oxygen uptake (with EC directly linked to this) from the measured HR. Time motion analysis included analysing worker's movement and the time spent on each movement through video analysis. In this case, the investigator analysed every second spent by each worker during

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every work shift[5]. This method has been well-received by the scientific community and could be implemented more frequently in the future because it is very precise and provides both qualitative and quantitative information on the work performed[21]. However, time-motion analysis is very time-consuming, since more than 20 hours are needed to record and analyse a single work shift[5]. Thus, large-scale assessments of workers across different agriculture jobs require significant personnel and financial resources.

Synthesis of quantitative data

We used data from all 61 studies, including a total of 1667 workers, to provide an estimated EC for each NACE code across the five selected industries via meta-analysis (Table 2) using the data reported in the studies of Table 1. Given that the physical characteristics of job types included in some NACE codes were overlapping, the data from all studies assessing EC in these jobs were merged to provide a single EC (Table 2). Details about the estimation of EC ~~for each NACE code is~~ are provided below, while the EC data of all the studied tasks for each of the five selected industries are illustrated in Figure 3. The EC data of all the tasks described below appear in an Appendix.

Indirect calorimetry was employed as an EC assessment method in a total of 44 studies as follows: 14 studies in agriculture[22-35], 5 studies in construction[36-40], 14 studies in manufacturing[41, 23, 42-51] (some papers include more than one study), and 13 studies in transportation [22, 52-63]. The heart rate monitoring method was used to assess workers' EC in 10 studies as follows: one study in the tourism industry[64], seven studies in the manufacturing industry[65-71], and two studies in the transportation industry[72, 73]. Time motion analysis was used as an EC assessment method in three studies as follows: one study in the tourism industry[74]

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and two studies in the agriculture industry[27, 5]. Detailed information about the estimation of EC and the specific tasks assessed in each study for each NACE code is provided in the Appendix.

DISCUSSION

Our aim in this review was to provide a detailed list of EC estimations in jobs within five major industries: (i) tourism (i.e., accommodation and food services), (ii) agriculture, (iii) construction, (iv) manufacturing, and (v) transportation. For standardization purposes, we used the statistical classification of economic activities in the European Community[16], which includes 35 different job types (i.e., NACE codes) within these five industries. Through our research, which included searching through a multitude of specialized papers published across 108 years, we were able to identify EC values for all targeted job types.

The EC estimates suggest that agriculture includes the most energy-demanding jobs among the five selected industries, with an average EC of 6.0±2.5 kcal/min for male and 2.9±1.0 kcal/min for female workers. The tasks with the highest EC estimates within agriculture included digging, weeding, mowing, threshing and picking. Jobs in the construction industry were the 2nd most demanding in terms of EC, with an average of 4.9±1.6 kcal/min for male workers (no data were found for female construction workers). Tasks such as shoveling and miscellaneous earthworks were the most physically demanding within the construction sector. The industry including the 3rd highest EC estimate was manufacturing with an average of 3.8±1.1 kcal/min for male and 3.0±1.3 kcal/min for female workers. It is important to note that manufacturing includes jobs with a wide range in EC estimates. For instance, jobs in coke, wood, paper, and basic metal plants show an average EC of 5.2±0.9 kcal/min, while jobs in leather and mineral product manufacturing have an average EC of 2.7±0.2 kcal/min. The transportation industry presented relatively moderate estimates of EC (average value 3.2±1.0 kcal/min for male workers) with land transport and postal activities having the highest (average EC: 3.9±0.1 kcal/min) and air transport activities the lowest EC requirements (average EC: 1.8±0.4

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kcal/min). Finally, jobs within the tourism industry demonstrated the lowest EC values among the five selected industries, with an average EC of 2.5±0.9 kcal/min. The above energy-demanding classification of industries is important since it indicates that the workers' energy cost can vary substantially among different jobs and industries and there is a need for a more specialized approach for each type of work. Occupational health services should take into consideration this variability when promoting methods and tools to protect workers' health and enhance their physical, mental, and social well-being, as well as in preventing ill-health and accidents.

An interesting aspect of the present analysis stems from the time emergence of the identified studies. During the pre-World War II period, the average number of relevant studies published per year was 0.22. The publications/year increased to 0.83 in the period 1946-1975 and then declined again to 0.56 in the period 1977-2007, only to rise to 0.9 during the past 10 years. This appears consistent with the history of the global economic growth during the 20th and 21st centuries[75)] and, thus, the need to assess workers' health, performance, and productivity. Indeed, the first decades of the 20th century was characterized by rapid technological change but also by economic instability and crisis[75)]. By the late 1930s, recovery was underway, but industrial production was, once again, disrupted due to World War II[75)]. The period 1946-1975, was a time of rapid change and economic growth which[76)] was followed by a period of economic/industrial slowdown and then, from the mid-1990s, the era of the "New Economy"[77)]. Therefore, it seems logical to postulate that the intensification of economic/industrial growth in the mid-twentieth century generated the need to measure human EC with the aim of improving workers' efficiency, health, and safety. Nevertheless, it is important to note that the physical demands of many jobs in the studied industries have changed markedly since those times. Therefore, an update of the EC estimates in these occupations is needed, especially since several guidelines and standards are using this knowledge.

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During the past 10 years, a renewal of interest regarding occupational EC has been observed which is fuelled by technological developments in wireless communication and miniaturized sensors. Another potential source for the renewed interest in this research field may stem from a shift in the load that workers are expected to perform today due to globalization in combination with national objectives for competitiveness and economic growth[78)]. As a result, several health-related issues have emerged in occupational settings, such as burn-out syndrome[4)] and work exhaustion[3)], that need to be considered. In addition, one of the most immediate and obvious effects of climate change is the increase in environmental temperatures and workers are already affected since many workplaces are becoming very hot[79, 5)]. Heat stress in occupational settings leads to reduced labour effort and productivity loss with detrimental effects on economic growth[80)]. Therefore, an updated analysis looking for an optimal compromise between workers' physiological capacity and the demands of the job, in combination with indoor/outdoor environmental conditions, is urgently needed. The EC estimation of an extensive range of different occupational settings is a necessary component in health and safety calculations/assessments according to guidelines aiming to preserve workers' health and wellbeing.

Despite our best intentions, it is important to note that the EC estimates provided in this paper should be considered through the prism of certain limitations. For instance, while some studies (e.g., Bielski,1976[69)], Brun,1979[30)], and Abdelhamid, 2002[40)]) provide a comprehensive description of several tasks included in each job, other papers (e.g., Inoue, 1955[65)], Davies, 1976[29)], and Moharana, 2013[64)]) provide only a single-phrase description or a job title. While we addressed the fact that the number of workers assessed in each study were different, by weighing the EC estimates provided for each NACE code, it is important to note that most of the studies assessed few or no women workers. As a consequence, we were only able to report EC estimates for women workers in 16 out of the 35 (45.7%) jobs studied. We attempted to assess

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the quality of the different studies and to weigh their effects against each other based on their quality, the 95% confidence intervals provided, and the heterogeneity of the data (e.g., by using the I^2 statistic, funnel plots, and the software such as RevMan). Unfortunately, this was not possible because the vast majority of job tasks in the analyzed studies were assessed by only one or two studies for each sex. Even when this was not true, the participants, methods to assess EC, and precise job descriptions varied considerably between studies. For instance, as shown in eTables 1a-c, the job task "weeding" has been reported by Benedict[22)] during gardening, by Kahn[25)] during cereal farming, by Edholm[34)] during vineyard farming/viticulture, by Brun[32)] during cotton farming, by de Guzman[60)] during rice farming, as well as Costa[33)] during apple farming. It becomes evident that, even in this case – where several studies assessed the same job task – a forest plot weighing the different studies would be inappropriate. Finally, all studies included in this review have been conducted in field settings/workplaces and, thus, it is logical to assume workers have been assessed while wearing normal work uniform. However, it is important to mention that the provided EC values may underestimate the true EC by 2.4-20.9% when added (i.e., more than that worn in typical workplaces) protective clothing is worn[81)].

CONCLUSION

In this paper we provide a detailed list of EC estimates in jobs within five major industries: (i) tourism (i.e., accommodation and food services), (ii) agriculture, (iii) construction, (iv) manufacturing, and (v) transportation. It is hoped that this information will aid the development of future instruments and guidelines aiming to protect workers' health, safety, and productivity by, for instance, helping to determine the tolerance limits for daily energy expenditure during the working hours. Future research should provide updated EC estimates in these jobs within a wide spectrum of occupational settings taking into account the sex, age, and physiological

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characteristics of the workers as well as the individual characteristics of each workplace. Assessing and quantifying the physical demands associated for each job task within an industry is key to fully understanding the requirements of working safely and without risks.

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Table 1. Job types in each industry, workers studied, and EC assessment method in all studies included in this review.

Industry	Study	Job type	Workers	EC assessment method
Tourism	Moharana, 2013[64]	Hotel (kitchen, housekeeping, laundry)	78 *	Heart rate monitoring
	Wills, 2016[74]	Restaurant work	5 ♂ / 15 ♀	Time motion analysis
Agriculture	Benedict, 1909[22]	Gardening	3 ♂	Indirect calorimetry
	Farkas, 1932[23]	Cereal farming	15 ♂	Indirect calorimetry
	Kahn, 1933[25]	Cereal farming	4 ♂ / 5 ♀	Indirect calorimetry
	Glaser, 1952[26]	Lumberjack	1 ♂	Indirect calorimetry
	Hettinger, 1953[27]	Cow milking	1 ♂	Time motion analysis
	Hettinger, 1953[27]	Ploughing	7 ♂	Indirect calorimetry
	Philips, 1954[28]	Gardening	7 ♂	Indirect calorimetry
	Edholm, 1973[34]	Vineyard farming / Viticulture	39♂ / 6 ♀	Indirect calorimetry
	Davies, 1976[29]	Sugar cane farming	42 ♂	Indirect calorimetry
	Brun,1979[30]	Cotton farming	45 ♂	Indirect calorimetry
	Nag, 1980[31]	Seeding	5 ♂	Indirect calorimetry
	Brun,1981[32]	General farming	30 ♂	Indirect calorimetry
	de Guzman, 1984[35]	Rice farming	10 ♂ / 10♀	Indirect calorimetry
	Brun, 1992[24]	General farming	132♀	Indirect calorimetry
	Costa, 1989[33]	Apple farming	17 ♂	Indirect calorimetry
	Ioannou, 2017[5]	Grape-picking	4 ♂ / 2 ♀	Time motion analysis
Construction	Baader, 1929[36]	General construction	1 ♂	Indirect calorimetry
	Müller, 1958[37]	Earthworks	2 ♂	Indirect calorimetry
	Ilmarinen, 1980[38]	General construction	21 ♂	Indirect calorimetry
	Almero, 1984[39]	General construction	25 ♂	Indirect calorimetry
	Abdelhamid, 2002[40]	General construction	18 ♂	Indirect calorimetry
Manufacturing	Greenwood, 1919[47]	Munition industry	52 ♀	Indirect calorimetry
	Kagan, 1928[50]	Machinery assembly	9 ♂	Indirect calorimetry
	Farkas, 1932[23]	Tailor industry	2 ♂	Indirect calorimetry
	Lehman, 1950[43]	Leather industry	10 ♂	Indirect calorimetry
	Lehman, 1950[43]	Printing industry	4 ♂	Indirect calorimetry
	Lehman, 1950[43]	Press goods industry	6 ♂	Indirect calorimetry
	Inoue, 1955[65]	Paper industry	6 ♂	Heart rate monitoring
	Turner, 1955[45]	Plastic and ebonite moulding	158 ♂	Indirect calorimetry
	Ford,1958[68]	Metal industry	26 ♂	Heart rate monitoring
	Raven, 1973[46]	Aluminium smelting industry	8 ♂	Indirect calorimetry
	Bielski,1976[69]	Furniture industry	10 ♂	Heart rate monitoring
	Aunola,1979[49]	Machine and tool manufacturing	190 ♂ / 47 ♀	Indirect calorimetry
	Vankhanen, 1978[44]	Coke industry	57 *	Indirect calorimetry
	de Guzman, 1979[42]	Textile industry	25 ♂ / 14 ♀	Indirect calorimetry
	Kerimova,1987[51]	Oil wells repairing	3 ♂	Indirect calorimetry
	Bortkiewicz, 2006[41]	Food industry	18 ♂ / 26 ♀	Indirect calorimetry
	Dowell, 2009[66]	Glass industry	18 ♂	Heart rate monitoring
	Biswas, 2012[67]	Aluminium industry	17 ♂	Heart rate monitoring
	Kalantary, 2015[70]	Automotive industry	42 ♂	Heart rate monitoring
	De la Riva, 2016[71]	Automotive industry	32 ♂ / 23 ♀	Heart rate monitoring
	Durnin, 1967[82]	Wood industry	ND	ND
	Durnin, 1967[82]	Chemical industry	ND	ND
	Bliss, 1964[48]	Electrical industry	36 ♂	Indirect calorimetry
Transportation	Benedict, 1909[22]	Car driving	3 ♂	Indirect calorimetry
	Benedict, 1909[22]	Motorcycle driving	3 ♂	Indirect calorimetry
	Crowden, 1941[63]	Postal work	4 ♂	Indirect calorimetry
	Karpovich, 1946[53]	Aircraft piloting	27 ♂	Indirect calorimetry
	Corey, 1948[54]	Aircraft piloting	10 ♂	Indirect calorimetry
	Lehman, 1959[61]	Transportation equipment cleaning	7 ♀	Indirect calorimetry
	Das,1966[58]	Load carrying	6 ♂	Indirect calorimetry

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Littell,1969[55]	Aircraft piloting	16 ♂	Indirect calorimetry
Rohmert, 1974[62]	Postal work	34 ♂	Indirect calorimetry
Malhotra,1976[52]	Submarine sailing	24 ♂	Indirect calorimetry
de Guzman et al,1978[60]	Office work	10 ♂ / 10 ♀	Indirect calorimetry
Samanta,1987[59]	Load carrying	5 ♂	Indirect calorimetry
Thornton,1984[56]	Aicraft piloting	12 ♂	Indirect calorimetry
Theurel, 2008[72]	Postal work	14 ♂	Heart rate monitoring
Pradhan, 2017[73]	Bus driving	48 ♂	Heart rate monitoring

Note: * = the sex distribution information is not provided. Moharana, 2013[64] were contacted but did not reply to queries.
Key: EC = energy cost; ♂ = males; ♀ = females; ND = no data provided.

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Table 2. Estimated energy cost for each NACE description across the five industries.

Industry	NACE code and description		Energy cost	
			kcal/min	Watts[1]
Tourism	I55	Accommodation	3.132±0.269 (♂♀)	218(♂♀)
	I56	Food and beverage service activities	1.916±0.630 (♂♀)	134 (♂♀)
Agriculture	A	Agriculture, forestry and fishing	6.022±2.52 (♂) / 2.879±1.01 (♀)	420 (♂) / 200 (♀)
Construction	F41-F43	Construction of buildings, civil engineering, specialised construction activities	4.950±1.58 (♂)	345 (♂)
Manufacturing	C10-C12	Manufacture of food products, beverages & tobacco products	3.020 (♂) / 2.030 (♀)[2]	210 (♂) / 142 (♀)[2]
	C13-C14	Manufacture of textiles and wearing apparel	2.903±0.60 (♂) / 1.743±0.54 (♀)	202(♂) / 122(♀)
	C15	Manufacture of leather and related products	2.850±0.21 (♂)	200 (♂)
	C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	4.130±0.68 (♂)	288 (♂)
	C17	Manufacture of paper and paper products	5.420±1.24 (♂)	378 (♂)
	C18	Printing and reproduction of recorded media	2.90±1.06 (♂)	202 (♂)
	C19	Manufacture of coke and refined petroleum products	6.35 (♂) / 5.52 (♀)[3]	443 (♂) / 385 (♀)[3]
	C20-C21	Manufacture of chemicals and chemical products and basic pharmaceutical products	4.86±1.25 (♂)	339 (♂)
	C22	Manufacture of rubber and plastic products	3.92±1.05 (♂)	273 (♂)
	C23	Manufacture of other non-metallic mineral products	2.58±2.21 (♂)	180 (♂)
	C24	Manufacture of basic metals	5.052±1.01 (♂)	352 (♂)
	C25	Manufacture of fabricated metal products, except machinery and equipment	2.51±0.90 (♂) / 3.59±0.76 (♀)	175 (♂) / 250 (♀)
	C26-C27	Manufacture of computer, electronic and optical products and electrical equipment	3.65±0.87 (♂)	255 (♂)
	C28	Manufacture of machinery and equipment	3.263±0.86 (♂) / 2.20±0.82 (♀)	228 (♂) / 153 (♀)
	C29-C30	Manufacture of motor vehicles, trailers & semi-trailers and other transport equipment	3.367±0.73 (♂) / 2.82±0.67 (♀)	235 (♂) / 197 (♀)
	C31	Manufacture of furniture	3.090 (♂)[4]	215 (♂)[4]
	C32	Other manufacturing	3.809±1.09 (♂) / 3.029±1.25 (♀)	266 (♂) / 211(♀)
	C33	Repair and installation of machinery & equipment	4.900±1.76 (♂)	342 (♂)
Transportation	H49	Land transport and transport via pipelines	3.811±0.55 (♂)	266 (♂)
	H50	Water transport	2.550±1.54 (♂)	178 (♂)
	H51	Air transport	1.847±0.40 (♂)	129 (♂)
	H52	Warehousing and support activities for transportation	3.619 ±2.27 (♂) / 2.367 ±1.66 (♀)	252 (♂) / 165 (♀)
	H53	Postal and courier activities	4.107 ±0.40 (♂)	286 (♂)

Note: [1] = kcal/min was converted into Watt using the formula 1 kcal/min = 69.78 Watts.
[2] = original results presented as range [(♂:2.50-3.54, ♀:1.56-2.50, kcal/min) (♂:174-247, ♀:109-174, Watts)];
[3] = original results presented as range [(♂:5.21-7.50, ♀:4.58-6.45, kcal/min) (♂:363-523, ♀:319-450, Watts)];
[4] = original results presented as range (♂:2.14-4.03, kcal/min; ♂:149-281, Watts).
Key: NACE = statistical classification of economic activities in the European Community (*Nomenclature statistique des activités économiques dans la Communauté Européenne*); ♂ = males; ♀ = females; ♂♀ = values apply to both males and females.

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Figure 1. Rectal temperature and fluid loss using the Predicted Heat Strain model for an individual performing light (e.g., light polishing; 207 Watts; grey line) or heavier (e.g., drilling; 476 W; black line) work with a hand tool for 8 hours while wearing typical work uniform with long sleeves in a thermoneutral (26°C air and radiant temperatures; 40% relative humidity) indoor (air velocity: 0.3 m/sec) environment.

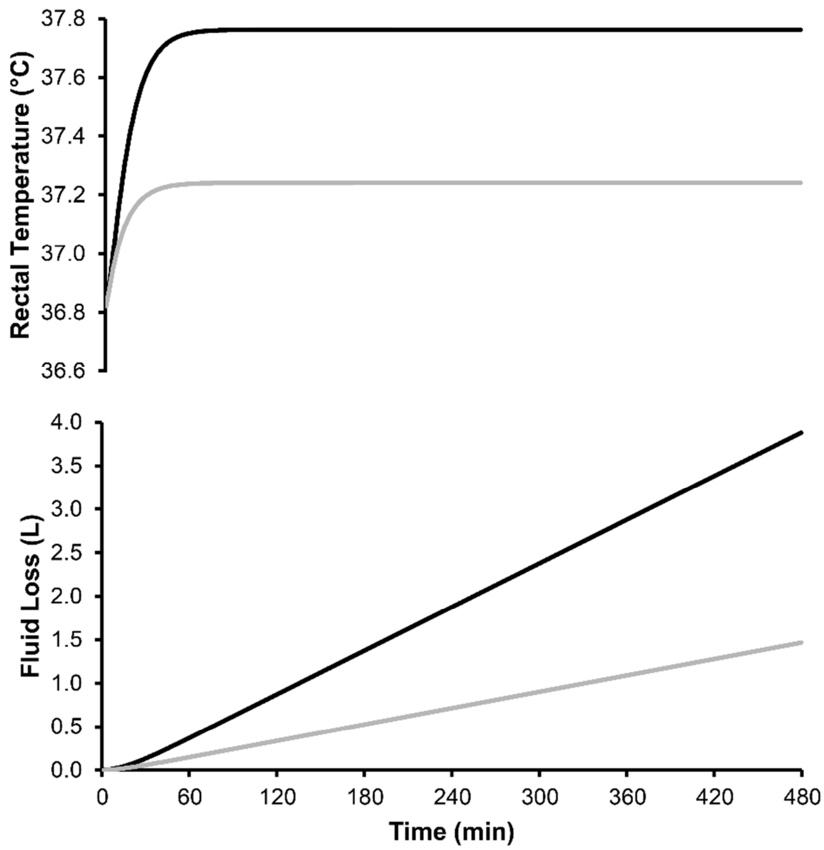

Figure 2. Chronological distribution of all the studies included in this review.

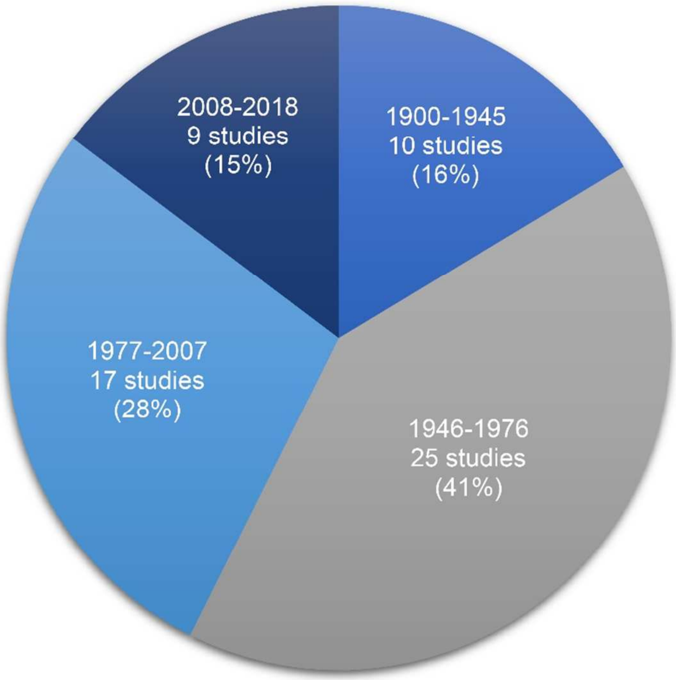

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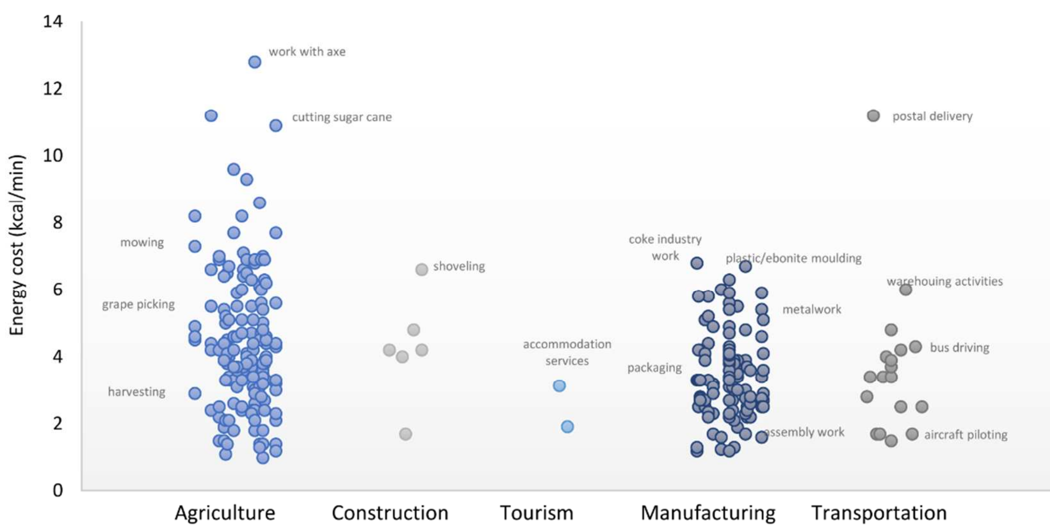
Figure 3. Average energy cost for each of the 325 tasks in the five selected industries which have been assessed in the 61 studied included in this analysis.



Review

Metabolic energy cost of workers in agriculture, construction, manufacturing, tourism, and transportation industries

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The aim of this study was to to review the existing literature and provide a detailed list of EC estimations in jobs/tasks included in five selected industries such as (i) accommodation and food services, (ii) agriculture, (iii) construction, (iv) manufacturing, and (v) transportation. This is important because the aforementioned five industries have a major impact in the global economy. For instance, together they represent 40% of the European Union's GDP and 50% of its workforce. A total of 63 studies were identified and 1667 workers were evaluated while performing a large number of tasks related to each one of the five selected industries. The averaged values for each NACE code (i.e., *Nomenclature statistique des activités économiques dans la Communauté européenne*; statistical classification of economic activities in the European Community)[1] appear in the main part of the manuscript. The energy cost data from all studies included in this review regarding each individual task type appear in the following tables. Details about the estimation of EC for each NACE code are provided below.

Tourism (i.e., Accommodation and food services activities) (I)

This sector is divided into 2 NACE codes [Accommodation (I55); Food services (I56)] corresponding to the job types assessed in two studies[2, 3] which monitored a total of 98 workers.

Accommodation (I55)

Moharana *et al.*[2] assessed the EC of 78 male and female hotel employees working in the kitchen, housekeeping, and laundry departments of a 3-star hotel using heart rate monitoring.

Food and beverage service activities (I56)

Wills *et al.*[3] monitored 5 male and 15 female servers during normal job duties in three different restaurants and estimated EC using time motion analysis.

Agriculture (A)

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The tasks included in this NACE code correspond to the job types assessed in 16 studies[4-18] which monitored a total of 230 male and 155 female workers. The EC is reported for many tasks including weeding, mowing wheat, ploughing and threshing[4, 5, 18, 6], working with axe, milking by hand/machine, ploughing, grass cutting, hoeing, load carrying, cutting cane, cotton harvesting, tending animals, seeding, spraying and mowing[7-14, 18], tractor driving, potato/orange picking, weeding, seeding, forking grass, harvesting, planting shoveling, plowing and spraying[15, 16], as well as grape-picking[17]. The EC data of all the aforementioned tasks appear in an Appendix and were averaged to provide a single sex-specific EC for this NACE code (Table 2 in main text).

Construction (F)

This sector is divided into 3 NACE codes [Construction of buildings (F41); Civil engineering (F42); Specialized construction activities (F43)] corresponding to the job types assessed in 5 studies[19-23] which monitored a total of 67 male workers. The EC is reported for many tasks including transporting concrete, cleaning up, removing panels, carrying, placing concrete, brick layering, loader operating, scaffolding, load carrying, mixing cement using shovel, tapping-chipping cement walls, shoveling sand, painting, and performing other miscellaneous earthworks[19-23]. The EC data of all the aforementioned tasks appear in an Appendix. Given that the physical characteristics of job types included in the three NACE codes were overlapping, the data from all five studies were merged to provide a single EC for the NACE codes F41-F43 (Table 2 in main text).

Manufacturing (C)

This sector is divided into 24 NACE codes (C10-C33) corresponding to the job types assessed in 23 studies[24-31, 5, 32-42] which monitored a total of 839 male and female

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workers. The EC data of all the relevant tasks appear in an Appendix. Given that the physical characteristics of job types included in some NACE codes were overlapping, the data from all studies assessing EC in these jobs were merged to provide a single EC (Table 2 in main text).

(i) Manufacture of food products (C10) / Manufacture of beverages (C11) / Manufacture of tobacco products (C12)

Bortkiewicz *et al.*[27] used indirect calorimetry to assess the EC of 44 workers from different departments of a foodstuff industry (Table 2 in main text).

(ii) Manufacture of textiles (C13) / Manufacture of wearing apparel (C14) / Manufacture of leather and related products (C15)

The EC of 51 workers is reported for several tasks in textile manufacturing including textile cutting, machine sewing, hand sewing and pressing[5], cloth cutting and inspecting, dyeing, washing-padding, weaving, creeling, counting yarns, warping, delivering and collecting boxes, spinning, walking[28], leather shoe manufacturing and repairing[43]. The data from all tasks were merged to provide a single EC (Table 2 in main text).

(iii) Manufacture of wearing of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials (C16)

Durnin and Passmore[31] report the EC of workers for several tasks in wood manufacturing including carpenter assembling and finishing, cabinet maker, laminating machine operator, milling machine operator, sanding machine operator, spray painter, wood stainer and packaging. The data from all tasks were merged to provide a single EC (Table 2 in main text).

(iv) Manufacture of paper and paper products (C17)

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Inoue *et al.*[33] used heart rate monitoring to assess the EC of six workers for many tasks in the paper industry including carrying paper machine parts, standing for long periods, working with hands above shoulder levels, and repairing a paper machine. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(v) Printing and reproduction of recorded media (C18)

Lehman *et al.*[43] used indirect calorimetry to assess the EC of 10 workers for several tasks in the printing and press good industries including handmade book composition, printing, paper layering, and book binding. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(vi) Manufacture of coke and refined petroleum products (C19)

Vankhanen *et al.*[41] used indirect calorimetry to assess the EC of 57 workers across the main departments of a coke-chemical plant (Table 2 in main text).

(vii) Manufacture of chemicals and chemical products (C20) / Manufacture of basic pharmaceutical products and pharmaceutical preparations (C21)

Durnin and Passmore[31] report the EC of workers for several tasks in the chemical industry including machine operation, oil refining, semi-skilled work, dispatch grinding, stirring machine operating, and stock room work. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(viii) Manufacture of rubber and plastic products (C22)

Turner *et al.*[39] used indirect calorimetry to assess the EC of 158 workers for several tasks in a plastic and ebonite industrial plant, including loading chemicals into a mixer, ebonite moulding, ebonite and plastic finishing, machine fitting, and cutting battery plates. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

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(ix) Manufacture of other non-metallic mineral products (C23)

Dowell *et al.*[30] used heart rate monitoring to assess the EC of 18 workers for several tasks in a glass manufacturing plant including manual work, work with one arm, work with both arms, and whole-body work. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(x) Manufacture of basic metals (C24)

The tasks included in this NACE code were assessed in two studies[38, 25] which monitored a total of 25 workers in the aluminium industry. The EC is reported for many tasks including crowbar/hammer work, handling metal, recovering molten metal[38] and cast box preparation, sand handling, metal handling, furnace operation and product finishing[25]. The EC data of all the aforementioned tasks appear in an Appendix and were averaged to provide a single EC estimate for this NACE code (Table 2 in main text).

(xi) Manufacture of fabricated metal products, except machinery and equipment (C25)

The tasks included in this NACE code were assessed in two studies[32, 40] which monitored a total of 78 workers in the munition and metal product industries. The EC is reported for many tasks including forging, stamping, tool setting, finishing copper bands, carrying loads, cleaning, drying[32] and metal product manufacturing[40]. The EC data of all the aforementioned tasks appear in an Appendix and were averaged to provide a single EC estimate for this NACE code (Table 2 in main text).

(xii) Manufacture of computer, electronic and optical products (C26) / Manufacture of electrical equipment (C27)

Bliss *et al.*[26] used indirect calorimetry to assess the EC of 36 workers for a variety of tasks in an electrical plant including armature winding, coil assembly, galvanizing,

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rolling machine operator, stock room work, and trimming. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(xiii) Manufacture of machinery and equipment n.e.c. (C28)

Aunola *et al.*[24] used indirect calorimetry to assess the EC of 237 workers for several tasks in the machinery and equipment industries including forging, welding, surface finishing, machine working and installation, assembly and inspection, storage and maintenance, as well as technical, sales, and office work. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(xiv) Manufacture of motor vehicles, trailers and semi-trailers / C30. Manufacture of other transport equipment (C29)

The tasks included in this NACE code were assessed in two studies[29, 35] which monitored a total of 97 workers in the automotive industry. The EC is reported for many tasks including heavy pressing, manual pressing, metalworking, and administration work[35] as well as cable cutting, pressing, manual assembly, assembly on board, taping operation, electrical testing, quality inspection, and material handling[29]. The EC data of all the aforementioned tasks appear in an Appendix and were averaged to provide a single EC estimate for this NACE code (Table 2 in main text).

(xv) Manufacture of furniture (C31)

Bielski *et al.*[42] used heart rate monitoring to assess the EC of 10 workers for several tasks in a furniture manufacturing plant, including sizing saw, cross cut saw, oscillating single spindle mortising machine, spindle moulder, thickness planer, and edge gluing press chain. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(xvi) Other manufacturing (C32)

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The average of all EC values reported across the 23 NACE codes (C10-C33) in the manufacturing industry was used as an estimate for this NACE code.

(xvii) Repair and installation of machinery and equipment (C33)

Kagan *et al.*[34] used indirect calorimetry to assess the EC of nine workers for several tasks in an machinery assembly plant including working entirely by hand and when machines were put together on a conveyor system. Kerimova *et al* [36], used indirect calorimetry to assess the EC of three workers in the oils wells repairing industry. The EC data of all the aforementioned tasks appear in an Appendix and were averaged to provide a single EC estimate for this NACE code (Table 2 in main text).

Transportation (H)

This sector is divided into five NACE codes [Land transport and transport via pipelines (H49); Water transport (H50); Air transport (H51); Warehousing and support activities for transportation (H52), as well as Postal and courier activities (H53)] corresponding to the job types assessed in 15 studies whichmonitored a total of 216 male and 17 female workers. The EC data of all the tasks for each job type appear in an Appendix.

(i) *Land transport and transport via pipelines (H49)*

The tasks included in this NACE code were assessed in two studies[4, 44] which monitored a total of 54 workers in land transportation. The EC is reported for many tasks including car, motorcycle, and bus driving[4, 44]. The EC data of all the aforementioned tasks appear in an Appendix and were averaged to provide a single EC estimate for this NACE code (Table 2 in main text).

(ii) Water transport (H50)

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Malhotra *et al.*[45], used indirect calorimetry to assess the EC of 24 workers for several tasks in submarine sailing including resting, reading/writing, standing, eating/drinking, equipment operation, action station, watch keeping, equipment cleaning, ascending and descending ladders, walking between compartments, loading and unloading, as well as ship cleaning. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(iii) Air transport (H51)

The tasks included in this NACE code were assessed in four studies[46-49] which used indirect calorimetry to evaluate a total of 65 workers during aircraft piloting. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(iv) Warehousing and support activities for transportation (H52)

This sector includes job types such as operating of transport infrastructure (e.g. airports, harbours, tunnels, bridges, etc.), activities of transport agencies and cargo handling[50]. The EC of 38 workers is reported for several tasks in warehousing and support activities and transportation industries including carrying load and manual lifting of loads[51, 52], office working[53] and cleaning transport facilities[37]. The data from all task were merged to provide a single EC estimate for this NACE code (Table 2 in main text).

(v) Postal and courier activities (H53)

Indirect calorimetry was used to assess the EC of workers in several tasks in postal and courier activities including mail sorting, office work and outside mail distribution[54-56]. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

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eTable 1(a). Breakdown of job types, energy cost, and workers' sex in all agriculture studies included in this review.

Agriculture study (job type)	Task type	Energy cost kcal/min	Energy cost Watts[1]	Assessed workers' sex
Benedict, 1909[4] (gardening)	Gardening, weeding	4.4	307	(♂)
	Gardening, weeding	5.6	390	(♂)
	Gardening, digging	8.6	600	(♂)
Farkas, 1932[5] (cereal farming)	Mowing wheat	7.7	537	(♂)
	Mowing barley	7.0	488	(♂)
	Setting up stooks	6.6	460	(♂)
	Binding wheat	7.3	509	(♂)
Kahn, 1933[6] (cereal farming)	Ploughing	6.9	481	(♂)
	Ploughing	5.4	376	(♂)
	Thrashing rye	5.0	349	(♂)
	Thrashing rye	4.5	314	(♂)
	Binding oats	3.3	230	(♀)
	Binding oats	4.1	286	(♀)
	Binding rye	4.2	293	(♀)
	Binding rye	4.7	327	(♀)
	Weeding rape	3.3	230	(♀)
Glaser, 1952[7] (lumberjack)	Working with axe	12.8	890	(♂)
Hettinger, 1953[8] (cow milking)	Milking by hand	4.7	327	(♂)
	Machine milking 1 pail	3.4	237	(♂)
	Machine milking 2 pails	3.9	272	(♂)
	Cleaning milk pails	4.4	307	(♂)
Hettinger, 1953[8] (ploughing)	Horseploughing	5.9	411	(♂)
	Horseploughing	5.1	355	(♂)
	Tractor ploughing	4.2	293	(♂)
	Tractor ploughing	4.2	293	(♂)
Philips, 1954[9] (gardening)	Grass cutting	4.3	300	(♂)
	Bush clearing	6.1	425	(♂)
	Hoeing	4.4	307	(♂)
	Head planning, load 20 kg	3.5	244	(♂)
	Log carrying	3.4	237	(♂)
	Tree felling	8.2	572	(♂)
Edholm, 1973[15] (vineyard farming / viticulture)	Tractor driving	2.2	153	(♂)
	Truck driving	1.9	132	(♂)
	Horse-cart driving	2.1	146	(♂)
	Potato picking	6.5	453	(♂)
	Potato, filling sacks on truck	3.4	237	(♂)
	Potato, load sacks on truck	9.3	649	(♂)
	Potato grading	3.1	216	(♂)
	Orange picking	3.7	258	(♂)
	Weeding	3.0	209	(♂)
	Carrots, picking	2.6	181	(♂)
	Seed casting	4.5	314	(♂)
	Spray insecticide	5.0	349	(♂)
	Manure spreading	6.3	439	(♂)
	Prune vines	4.0	279	(♂)
	Scythe grass	5.9	411	(♂)
	Fork grass	6.0	418	(♂)
	Irrigation pipes, move	7.7	537	(♂)
	Weeding	3.3	230	(♀)
	Scything	11.2	781	(♀)
	Top carrots	2.1	146	(♀)
	Fork grass	4.5	314	(♀)
Davies, 1976[10] (sugar cane farming)	Cutting sugar cane	10.9	761	(♂)

Note: [1] = kcal/min was converted into Watts using the formula 1kcal/min = 69.78 Watts.

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eTable 1(b). Breakdown of job types, energy cost, and workers' sex in all agriculture studies included in this review.

Agriculture study (job type)	Task type	Energy cost kcal/min	Energy cost Watts[1]	Assessed workers' sex
Brun,1979[11] (cotton farming)	Picking cotton and carrying sack	3.6	251	(♂)
	Loading, collecting sacks on lorry	7.1	495	(♂)
	Opening/closing irrigation channels	4.5	314	(♂)
	Channel digging	7.0	488	(♂)
	Digging	6.4	446	(♂)
	Weeding	5.2	362	(♂)
	Tending threshing machine	3.8	265	(♂)
	Lifting grain sacks	4.0	279	(♂)
	Winnowing	4.0	279	(♂)
	Tending animals	5.1	355	(♂)
	Collecting and spreading manure	5.5	383	(♂)
	Loading manure	6.8	474	(♂)
	Riding donkey/tractor	2.9	202	(♂)
	Cycling on level dirt road	5.6	390	(♂)
Nag, 1980[12] (seeding)	Sitting, resting	1.0	69	(♂)
	Free walking on plane surface	2.7	188	(♂)
	Free walking on puddle field	3.3	230	(♂)
	Transplanting, bending on puddle field	3.1	216	(♂)
	Germinating seeder	8.2	572	(♂)
	Germinating seeder (IRRI type)	9.6	669	(♂)
	Manual threshing by beating	4.6	320	(♂)
	Pedal threshing	6.6	460	(♂)
	Pedal threshing, helper	3.2	223	(♂)
Brun,1981[13] (general farming)	Lying	1.4	97	(♂)
	Sitting	1.4	97	(♂)
	Standing	1.4	97	(♂)
	Walking	3.6	251	(♂)
	Walking slowly	2.9	202	(♂)
	Walking fast	4.2	293	(♂)
	Cycling	4.4	307	(♂)
	Sowing	3.9	272	(♂)
	Thinning out and replanting	3.8	265	(♂)
	Hoeing	5.1	355	(♂)
	Land clearing	6.9	481	(♂)
	Sorghum harvest: standing, cutting	2.4	167	(♂)
	Bent forward, uprooting potatoes	3.9	272	(♂)
	Plucking leaves and stems, standing	6.8	265	(♂)
	Kneeling and sorting, sweet potatoes	1.8	125	(♂)
	Cutting straw with a sickle, bent forward	5.6	390	(♂)
	Walking with a sheaf of straw on head	3.4	237	(♂)
	Pulling and breaking into pieces branches	3.8	265	(♂)
	Cutting wood with a machete	4.6	320	(♂)
	Unloading a cart of branches	3.6	251	(♂)
	Vine weaving	2.4	167	(♂)
	Hand weaving sitting on the ground	2.6	181	(♂)
	Hand sewing	1.8	125	(♂)
	Sewing with treadle sewing machine	2.4	167	(♂)
	Clay kneading	3.0	209	(♂)
	Sawing a calabash by hand, bending	3.1	216	(♂)
	Making mud bricks squatting	3.3	230	(♂)
	Standing, making a mud wall	1.8	125	(♂)
	Digging the earth with a pick-axe	6.4	446	(♂)
	Shovelling mud	4.9	341	(♂)

Note: [1] = kcal/min was converted into Watts using the formula 1kcal/min = 69.78 Watts.

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eTable 1(c). Breakdown of job types, energy cost, and workers' sex in all agriculture studies included in this review.

Agriculture study (job type)	Task type	Energy cost kcal/min	Energy cost Watts[1]	Assessed workers' sex
de Guzman, 1984[16) (rice farming)	Sitting	1.5	104	(♂)
	Standing	1.5	104	(♂)
	Walking	3.3	230	(♂)
	Weeding by hand	4.1	286	(♂)
	Mechanical weeding	6.7	467	(♂)
	Pushing hand tractor	6.5	453	(♂)
	Harvesting	4.4	307	(♂)
	Threshing	6.3	439	(♂)
	Winnowing	2.4	167	(♂)
	Plowing	6.9	481	(♂)
	Harrowing	6.9	481	(♂)
	Spray	5.4	376	(♂)
	Measuring harvested palay	6.9	481	(♂)
	Germinating palay	4.5	314	(♂)
	Carrying and stacking palay	5.5	383	(♂)
	Application of fertilizer	3.3	230	(♂)
	Planting	4.2	293	(♂)
	Mowing with a scythe	4.6	320	(♂)
	Carry palay	5.5	383	(♂)
	Sitting	1.2	83	(♀)
	Standing	1.3	90	(♀)
	Walking	2.3	160	(♀)
	Weeding	3.8	265	(♀)
	Harvesting	3.7	270	(♀)
	Threshing	4.6	320	(♀)
	Winnowing	2.5	174	(♀)
	Planting	3.9	272	(♀)
Brun, 1992[18) (general farming)	Sitting inactive	1.1	76	(♀)
	Standing resting	1.4	97	(♀)
	Squatting washing clothes	2.1	146	(♀)
	Standing hoeing	3.8	265	(♀)
	Bending, planting potatoes	3.4	237	(♀)
	Bending harvesting potatoes	2.3	160	(♀)
	Ploughing with buffalo	2.9	202	(♀)
	Standing sowing rice	2.1	146	(♀)
	Bending, transplanting rice	2.8	195	(♀)
	Bending, cutting rice	3.2	223	(♀)
	Squatting, bundling rice	2.4	167	(♀)
	Standing, threshing rice	3.9	272	(♀)
	Walking, carrying 30–35 kg	3.7	258	(♀)
	Walking, tapping rubber	2.5	174	(♀)
Costa, 1989[14) (apple farming)	Apple pruning	4.6	320	(♂)
	Weeding	6.0	418	(♂)
	Hand spray	4.8	334	(♂)
	Mech spray	2.4	167	(♂)
	Mowing	6.2	432	(♂)
	Picking	4.6	320	(♂)
Ioannou, 2017[17) (grape picking)	Grape-picking	4.7	327	(♂)
	Grape-picking	3.7	258	(♀)

Note: [1] = kcal/min was converted into Watts using the formula 1kcal/min = 69.78 Watts.

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eTable 2. Breakdown of job types, energy cost, and workers' sex in all construction studies included in this review

Construction study (job type)	Task type	Energy cost		Assessed workers' sex
		kcal/min	Watt[1]	
Baader, 1929[19) (general construction)	Making a wall with bricks, mortar at normal rates	4.0	279	(♂)
	Miscellaneous earthworks	1.7	118	(♂)
Müller, 1958[20) (earthworks)	Miscellaneous earthworks	4.8	335	(♂)
Ilmarinen, 1980[21) (general construction)	Striking/shoveling ground	6.6	460	(♂)
Almero, 1984[22) (general construction)	General labor, masonry, electricals, painting	4.2	293	(♂)
Abdelhamid, 2002[23) (general construction)	Transport concrete, cleaning up, placing concrete, removing layout/staking marks, assembling formwork, stacking, haul bricks/blocks, spread cleaning sand	4.2	293	(♂)

Note: [1] = kcal/min was converted into Watts using the formula 1kcal/min = 69.78 Watts.

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eTable 3(a). Breakdown of job types, energy cost, and workers' sex in all manufacture studies included in this review.

Manufacture study (job type)	Task type	Energy cost kcal/min	Energy cost Watts[1]	Assessed workers' sex
Greenwood, 1919[32] (munition industry)	Laboring	5.1	355	(♀)
	Cleaning and drying	4.9	341	(♀)
	Gauging	4.0	279	(♀)
	Walking and carrying	3.9	272	(♀)
	Finishing copper bands, tool setting	3.4	237	(♀)
	Heavy turning, hoisting shelf with pulley	3.3	230	(♀)
	Stamping	3.2	223	(♀)
	Forging	3.1	216	(♀)
	Turning and finishing	3.0	209	(♀)
	Light turning	2.5	174	(♀)
Kagan, 1928[34] (machinery assembly)	Working entirely by hand	5.8	404	(♂)
	Machines were put on a conveyor system	2.8	195	(♂)
Farkas, 1932[5] (tailor industry)	Cutting	2.5	174	(♂)
	Machine sewing	2.7	188	(♂)
	Hand sewing	1.9	132	(♂)
	Pressing	3.9	272	(♂)
Lehman, 1950[43] (leather industry)	Shoe repairing	2.7	188	(♂)
	Shoe manufacturing	3.0	209	(♂)
Lehman, 1950[43] (printing industry)	Printing industry: Hand compositor	2.2	153	(♂)
	Printer	2.2	153	(♂)
	Paper layer	2.5	174	(♂)
	Book-binder	2.3	160	(♂)
Lehman, 1950[43] (press goods industry)	Pressing household utensils	3.8	265	(♂)
Inoue, 1955[33] (paper industry)	Working with hands above shoulder level, heavy lifting, standing for long periods	5.4	376	(♂)
Turner, 1955[39] (plastic and ebonite moulding	Unloading battery boxes from oven	6.8	474	(♂)
	Loading chemicals into mixer	6.0	418	(♂)
	Machine moulding battery plates	5.1	355	(♂)
	Casting lead balls in mould	4.8	334	(♂)
	Straightening lead contact bars	4.6	320	(♂)
	Rimming battery plates	4.4	307	(♂)
	Heavy battery plate casting	4.2	293	(♂)
	Machine fitting	4.2	293	(♂)
	Lead rolling on roller mill	3.9	272	(♂)
	Loading plates into charging vat	3.9	272	(♂)
	Moulding ebonite	3.6	251	(♂)
	Light. battery plate casting	3.6	251	(♂)
	Tool room workers	3.9	272	(♂)
	Turners	3.7	258	(♂)
	Joiners	3.6	251	(♂)
	Cutting battery plates	3.3	230	(♂)
	Plastic moulding	3.3	230	(♂)
	Punching battery plates to size	3.3	230	(♂)
	Machinists (engineering)	3.1	216	(♂)
	Sheet metal worker	3.0	209	(♂)
	Joiner trainee	3.0	209	(♂)
	Medium assembly work	2.7	188	(♂)
	Typewriter mechanic trainee	2.1	146	(♂)
Ford,1958[40] (metal industry)	Metal product manufacturing	2.5	174	(♂)

Note: [1] = kcal/min was converted into Watts using the formula 1kcal/min = 69.78 Watts.

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eTable 3(b). Breakdown of job types, energy cost, and workers' sex in all manufacture studies included in this review.

Manufacture study (job type)	Task type	Energy cost kcal/min	Energy cost Watts[1]	Assessed workers' sex
Raven, 1973[38] (aluminium smelting industry	Using automatic crowbar, break crust with hand jack hammer, remove cover over pots, placing carbon	4.1	286	(♂)
Bielski et al.,1976[42] (furniture industry)	Sawing, belt sanding, machine, drum sander, oscillating mortising machine, spindle moulder, conveyor system, hydraulic press	3.1	216	(♂)
Aunola et al.,1979[24] (machine and tool manufacturing)	Foundry work, forging, welding, surface finishing, machine working, installation, assembly, inspection, storage, office	3.3/2.2	230/153	(♂♀)
Vankhanen, 1978[41] (coke industry)	Coke industry work	6.3/5.5	439/383	(♂♀)
de Guzman, 1979[28] (textile industry)	Sitting	1.2/1.2	83/83	(♂♀)
	Standing	1.3/1.2	90/83	(♂♀)
	Walking	3.2/2.6	223/181	(♂♀)
	Ringframe spinning	2.6/1.9	181/132	(♂♀)
	Conewinding	3.6/1.9	251/132	(♂♀)
	Warping	3.2/1.5	223/104	(♂♀)
	Weaving	3.6/1.9	251/132	(♂♀)
	Delivering and collecting boxes	5.2	362	(♂)
	Pinwinding	3.3	230	(♂)
	Loading of warp beam	5.8	404	(♂)
	Counting yarns per dent	2.4	167	(♂)
	Creeling	3.4	237	(♂)
	Weaving	3.5	244	(♂)
	Cloth cutting	4.1	286	(♂)
	Writing (sitting activity)	1.3	90	(♂)
	Washing-padding	2.4	167	(♂)
	Releasing and dye mixing	2.6	181	(♂)
	Gig dyeing 2	2.7	188	(♂)
	Backtending or high-curing	1.7	118	(♂)
	Cloth inspecting	1.2	83	(♂)
Kerimova,1987[36] (oils wells repairing)	Oils wells repairing	6.7	474	(♂)
Bortkiewicz, 2006[27] (food industry)	Food manufacture process	3.0/2.0	209/139	(♂/♀)
Dowell, 2009[30] (glass industry)	Sitting	0.3	20	(♂)
	Standing	0.6	41	(♂)
	Walking	2.0-3.0	139/209	(♂)
	Manual work	0.7	48	(♂)
	Work, one arm	1.6	111	(♂)
	Work, both arms	2.2	153	(♂)
	Work, whole body	2.7	188	(♂)
Biswas, 2012[25] (aluminium industry)	Cast box preparation, sand handling, metal handling, furnace operation, product finishing	5.5	383	(♂)
Kalantary, 2015[35] (automotive industry)	Heavy pressing, manual pressing, metalworking, administrative work	3.8	365	(♂)
De la Riva, 2016[29] (automotive industry)	Cable cutting, pressing, assembly, taping operation, electrical testing, quality inspection, material handling	2.8	195	(♂♀)
Durnin, 1967[31] (wood industry)	Carpenter -assembling	3.9	272	(♂)
	Carpenter-finishing	2.9	202	(♂)
	Cabinet maker	5.6	390	(♂)
	Laminating machine operator	4.0	279	(♂)
	Milling machine operator	3.8	265	(♂)
	Sanding machine operator	4.3	300	(♂)
	Spray painter	3.9	272	(♂)
	Wood stainer	4.7	327	(♂)

Note: [1] = kcal/min was converted into Watts using the formula 1kcal/min = 69.78 Watts.

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eTable 3(c). Breakdown of job types, energy cost, and workers' sex in all manufacture studies included in this review

Manufacture study (job type)	Task type	Energy cost kcal/min	Energy cost Watts[1]	Assessed workers' sex
Durnin, 1967[31)] (chemical industry)	Machine operator-oil refining	3.6	251	(♂)
	Despatch	3.6	251	(♂)
	Grinding	4.9	341	(♂)
	Stirring machine operator	5.9	411	(♂)
	Stock room work	6.3	439	(♂)
Bliss, 1964[26)] (electrical industry)	Armature winding	2.2	153	(♂)
	Battery plate casting	3.9	272	(♂)
	Battery plate punching and cutting	3.4	237	(♂)
	Coil assembly	4.0	279	(♂)
	Dipper	5.4	376	(♂)
	Ebonite moulding	3.4	237	(♂)
	Galvanizing	4.7	327	(♂)
	Materials handling	3.3	230	(♂)
	Punch press operator	4.2	293	(♂)
	Relay	2.3	160	(♂)
	Radio mechanics	2.7	188	(♂)
	Rolling machine operator	2.7	188	(♂)
	Stock room work	4.2	293	(♂)
	Trimming	4.2	293	(♂)
	Wire drawing machine operator	4.1	286	(♂)

Note: [1] = kcal/min was converted into Watts using the formula 1kcal/min = 69.78 Watts.

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Table 4. Breakdown of job types, energy cost, and workers' sex in all transportation studies included in this review

Transportation study (job type)	Task type	Energy cost kcal/min	Energy cost Watts[1]	Assessed workers' sex
Benedict, 1909[4)] (land transportation)	Driving a car	2.8	195	(♂)
Benedict, 1909[4)] (land transportation)	Driving a motor cycle	3.4	237	(♂)
Crowden, 1941[57)] (postal work)	Postal delivery, climbing stairs at usual pack	4.0	279	(♂)
Karpovich, 1946[46)] (air transportation)	Airplane piloting	1.7	118	(♂)
Corey, 1948[47)] (air transportation)	Airplane piloting	1.7	118	(♂)
Lehman, 1959[37)] (cleaning transport facilities)	Sweeping inside a tram	3.4	237	(♀)
	Washing inside and outside of trams	4.0	279	(♀)
	Washing car	3.4	237	(♀)
	Sweeping in a hall	4.2	293	(♀)
Das,1966[51)] (cargo)	Load carrying 27 kg	6.0	428	(♂)
Littell,1969[48)] (air transportation)	Aircraft piloting (light helicopter, utility helicopter, medium helicopter, fixed wing utility helicopter)	1.7	118	(♂)
Rohmert, 1974[54)] (postal work)	Distribute letters, recording discard, empty bag, load/undload the bags in the wagon, repack and stow bag in cargo	4.3	300	(♂)
Malhotra,1976[45)] (water transportation)	Submarine sailing	2.5	174	(♂)
de Guzman,1978[53)] (transportation support activities)	Office work	1.6/1.4	111/97	(♂/♀)
Samanta,1987[52)] (warehousing)	Load carrying	4.8	544	(♂)
Thornton,1984[49)] (air transportation)	Helicopter piloting	2.5	174	(♂)
Theurel, 2008[55)] (postal work)	Postman work	3.7	258	(♂)
Pradhan, 2017[44)] (land transportation)	Bus driving	3.9	272	(♂)

Note: [1] = kcal/min was converted into Watts using the formula 1kcal/min = 69.78 Watts.

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Metabolic energy cost of workers in agriculture, construction, manufacturing, tourism, and transportation industries

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ABSTRACT

The assessment of energy cost (EC) at the workplace remains a key topic in occupational health due to the ever-increasing prevalence of work-related issues. This review provides a detailed list of EC estimations in jobs/tasks included in tourism, agriculture, construction, manufacturing, and transportation industries. A total of 61 studies evaluated the EC of 1667 workers while performing a large number of tasks related to each one of the aforementioned five industries. Agriculture includes the most energy-demanding jobs (males: 6.0±2.5 kcal/min; females: 2.9±1.0 kcal/min). Jobs in the construction industry were the 2nd most demanding (males: 4.9±1.6 kcal/min; no data for females). The industry with the 3rd highest EC estimate was manufacturing (males: 3.8±1.1 kcal/min; females: 3.0±1.3 kcal/min). Transportation presented relatively moderate EC estimates (males: 3.1±1.0 kcal/min; no data for females). Tourism jobs demonstrated the lowest EC values (2.5±0.9 kcal/min for males and females). It is hoped that this information will aid the development of future instruments and guidelines aiming to protect workers' health, safety, and productivity. Future research should provide updated EC estimates within a wide spectrum of occupational settings taking into account the sex, age, and physiological characteristics of the workers as well as the individual characteristics of each workplace.

Keywords: energy expenditure, work intensity, physical activity, workload, metabolic rate, labour, industry.

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INTRODUCTION

Energy cost (EC) of work is an important aspect of occupational health and exercise physiology. Initial studies on EC primarily aimed to generate guidelines for caloric/dietary needs[1)] or to determine the upper tolerance limits for daily energy expenditure during the working hours[2)]. Today, the assessment of EC remains a key topic in occupational health due to the ever-increasing prevalence of work-related issues including fatigue[3)], anxiety, and burn-out syndrome[4)] as well as the realization that metabolic heat can lead to significant health and productivity decrements[5)]. It is not surprising, therefore, that current occupational guidelines highlight the importance of EC assessment during work for the workers' health and safety, for prevention of physical and mental illness, as well as for the development of corrective action plans[6, 7)].

Information about the EC is even more important when the worker is wearing protective clothing, which inhibits the body's ability to dissipate heat and may increase the EC for an activity, and/or when he/she is working in a hot environment[5, 8)]. This is because the EC directly determines the heat generation in the body which needs to be dissipated to avoid excessive heat strain. For example, the Predicted Heat Strain model developed in the International Organization for Standarization (ISO) 7933 suggests that an individual [height :184 cm; weight: 84 kg; wearing typical work uniform with long sleeves (0.6 clo)] working for 8 hours indoors (air velocity: 0.3 m/sec) with a hand tool (light polishing; i.e., EC of 207 W/m^2 in a thermoneutral environment (26°C air and radiant temperatures; 40% relative humidity) is not estimated to reach a rectal temperature beyond 37.24°C and should consume ~1.5 L of fluid to remain hydrated (Figure 1). In contrast, the same individual performing heavier work with a hand tool (e.g., drilling; i.e., EC of 476 W/m^2) in the same environment while wearing the same uniform is estimated to reach a rectal temperature beyond 37.76°C and should consume ~3.9 L of fluid to remain hydrated (Figure 1).

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The importance of EC assessment is becoming increasingly pertinent due to the occurring climate change[8]. In this light, occupational health and safety recommendations and standards have been developed providing scale limits based on both environmental and metabolic data[9, 10]. For instance, the ISO has facilitated international coordination and unification of industrial standards[6] to predict the physiological strain from a stressful environment condition. The additional application of ISO standards (such as ISO 7243) provides Wet-bulb Globe Temperature (WBGT) reference values for a variety of environmental and physiological conditions (i.e. clothing and workload)[11]. Given the above, it is not surprising that the EC is a necessary component in health and safety calculations/assessments according to guidelines aiming to preserve workers' health and wellbeing[5, 6].

While a lot of data on EC[9] for different work activities have been collected and summarized in key publications[12] in the last century[13], given the changing work content those values for EC may not all be representative anymore for today's situation. A number of studies in the literature that are most recent have assessed the EC for jobs/tasks included in industries such as (i) tourism (i.e., accommodation and food services), (ii) agriculture, (iii) construction, (iv) manufacturing, and (v) transportation. However, these studies are scattered across a multitude of scientific journals and are very difficult to locate, especially by health and safety experts working in the industry who do not always have access to specialized journals. Ainsworth et al., 2011[14] have developed a classification system of energy cost of several physical activities including activities of daily living or self-care, leisure and recreation, occupation and rest. While this compendium of activities provides information based on published lists and selected unpublished data, the values of some activities were derived from laboratory studies and not actual measurements on workers during their work shift. Moreover, this compendium does not completely cover the aforementioned five industries which are important because they have a major impact in the global economy. For instance, together they represent 40% of the European

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Union's GDP and 50% of its workforce[15]. In this light, our aim in this study was to review the existing literature and provide an up-to-date detailed list of EC estimations in jobs included in (i) tourism, (ii) agriculture, (iii) construction, (iv) manufacturing, and (v) transportation.

METHODS

To identify relevant jobs across the five selected industries, we used the statistical classification of economic activities in the European Community (NACE; *Nomenclature statistique des activités économiques dans l Communauté européenne*; Rev. 2 (2008)[16]. We made every effort to conduct a systematic search, yet this was not possible since this method did not ensure that all the relevant jobs/tasks included in the 35 different NACE codes would be identified. Initial systematic searches resulted in a very small number of retrieved articles, most of which were not addressing our research question. In this light, two investigators (K.P. and A.D.F.) independently searched the PubMed and Google Scholar databases as well as the Google search engine for studies using the following keywords: "energy cost", "energy expenditure", "metabolic rate", "oxygen consumption", "heart rate", "work intensity", and "workload" in combination with job/task descriptions in the relevant NACE codes [agriculture, construction of buildings, food manufacturing, land transport, tourism (i.e., accommodation and food service), etc.]. Other than scientific rigor and quality (i.e., usage of reproducible and evidence-based methodologies), no limits were set regarding the publication type to ensure that all available information would be assessed. Thus, our search included books, research articles, reviews, reports, and conference proceedings. The retrieved list of the identified articles, reports, and books was screened by two investigators (K.P. and A.D.F.) to identify publications that were relevant to the topic under review.

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For each NACE code across the five selected industries, an estimated EC is provided via meta-analysis by averaging the data reported in the relevant studies. In cases where the EC for a job was not found during our literature search, we used the EC of an activity that was closely related or similar in type and intensity. It is important to note that the EC estimates provided by many studies are based on a significant number of workers but, for some NACE codes (e.g. some jobs within agriculture), the EC data are derived from a single study and/or from very few workers. To address this issue, the estimated EC for each NACE code was weighed based on the number of workers assessed in each study (as a function of the total number of workers assessed in all studies of that NACE code). Details about the estimation of EC for each NACE code is provided below.

The EC was expressed in kcal/min (when reported in kJ/min, PAR, kcal/shift, etc.) to allow for comparisons within and between industries, as well as in W to harmonize with the national and international standards of ergonomic assessment[6)]. Specifically, when EC values were expressed in kJ/min, the data were converted into kcal/min either using the power conversion formula $P_{[kcal/min]} = 0.239 \times P_{[kJ/min]}$. In cases where EC was expressed as "metabolic equivalent" units[14)], the data were converted to kcal/min using the definition of "metabolic equivalent" as the ratio of work metabolic rate to a standard resting metabolic rate of 1.0 kcal/kg/h. When heart rate was monitored as an indicator of EC, the data were converted to kcal/min using the previously-published equation[17)]: EC = gender × (-55.0969 + 0.6309 × heart rate + 0.1988 × weight + 0.2017 × age) + (1 – gender) × (-20.4022 + 0.4472 × heart rate – 0.1263 × weight + 0.074 × age), where gender is equal to 1 for males and 0 for females. When EC was given in kcal/shift, the values were divided by 3.600 minutes to convert into kcal/min. Finally, kcal/min was converted into W using the formula 1kcal/min = 69.78 W.

RESULTS

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Searching procedure results

A total of 61 studies were identified as relevant during the search and were considered for subsequent analysis. Of these, 33(54%) were identified via PubMed, 23(38%) were identified via Google Scholar, while 5 (8%) were identified via the Google search engine.

Characteristics of the included studies and qualitative synthesis

The 61 studies included in the analysis were published from 1909 to 2017 (the majority being published in the period 1946-1976; Figure 2) and included 1667 workers who were evaluated while performing a large number of tasks (tourism: 4 tasks; agriculture: 137 tasks; construction: 15 tasks; manufacturing: 148 tasks; transportation: 21 tasks) related to each one of the five selected industries. The job types, number and sex of workers assessed, as well as the EC assessment method in these 61 studies across the five industries are presented in chronological order in Table 1.

In the vast majority (79%) of the studies, indirect calorimetry was employed as an assessment method of workers' EC, while in 16% and 5% of the studies heart rate monitoring and time motion analysis methods were used, respectively. Indirect calorimetry implies that the worker's oxygen consumption was measured directly (EC to be calculated from this) using either collection of expired air in Douglas bags[18)] for later analysis or using portable gas analysis systems[19)] to determine oxygen uptake (and in some cases also CO2 production). Heart rate monitoring requires measurement of heart rate (HR)[20)] during the activity, and a separate 'calibration' of the worker's individual relation between HR and oxygen uptake to then deduct oxygen uptake (with EC directly linked to this) from the measured HR. Time motion analysis included analysing worker's movement and the time spent on each movement through video analysis. In this case, the investigator analysed every second spent by each worker during

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every work shift[5]. This method has been well-received by the scientific community and could be implemented more frequently in the future because it is very precise and provides both qualitative and quantitative information on the work performed[21]. However, time-motion analysis is very time-consuming, since more than 20 hours are needed to record and analyse a single work shift[5]. Thus, large-scale assessments of workers across different agriculture jobs require significant personnel and financial resources.

Synthesis of quantitative data

We used data from all 61 studies, including a total of 1667 workers, to provide an estimated EC for each NACE code across the five selected industries via meta-analysis (Table 2) using the data reported in the studies of Table 1. Given that the physical characteristics of job types included in some NACE codes were overlapping, the data from all studies assessing EC in these jobs were merged to provide a single EC (Table 2). Details about the estimation of EC are provided below, while the EC data of all the studied tasks for each of the five selected industries are illustrated in Figure 3. The EC data of all the tasks described below appear in an Appendix.

Indirect calorimetry was employed as an EC assessment method in a total of 44 studies as follows: 14 studies in agriculture[22-35], 5 studies in construction[36-40], 14 studies in manufacturing[41, 23, 42-51] (some papers include more than one study), and 13 studies in transportation [22, 52-63]. The heart rate monitoring method was used to assess workers' EC in 10 studies as follows: one study in the tourism industry[64], seven studies in the manufacturing industry[65-71], and two studies in the transportation industry[72, 73]. Time motion analysis was used as an EC assessment method in three studies as follows: one study in the tourism industry[74] and two studies in the agriculture industry[27, 5]. Detailed information about the estimation of EC and the specific tasks assessed in each study for each NACE code is provided in the Appendix.

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DISCUSSION

Our aim in this review was to provide a detailed list of EC estimations in jobs within five major industries: (i) tourism (i.e., accommodation and food services), (ii) agriculture, (iii) construction, (iv) manufacturing, and (v) transportation. For standardization purposes, we used the statistical classification of economic activities in the European Community[16)], which includes 35 different job types (i.e., NACE codes) within these five industries. Through our research, which included searching through a multitude of specialized papers published across 108 years, we were able to identify EC values for all targeted job types.

The EC estimates suggest that agriculture includes the most energy-demanding jobs among the five selected industries, with an average EC of 6.0±2.5 kcal/min for male and 2.9±1.0 kcal/min for female workers. The tasks with the highest EC estimates within agriculture included digging, weeding, mowing, threshing and picking. Jobs in the construction industry were the 2nd most demanding in terms of EC, with an average of 4.9±1.6 kcal/min for male workers (no data were found for female construction workers). Tasks such as shoveling and miscellaneous earthworks were the most physically demanding within the construction sector. The industry including the 3rd highest EC estimate was manufacturing with an average of 3.8±1.1 kcal/min for male and 3.0±1.3 kcal/min for female workers. It is important to note that manufacturing includes jobs with a wide range in EC estimates. For instance, jobs in coke, wood, paper, and basic metal plants show an average EC of 5.2±0.9 kcal/min, while jobs in leather and mineral product manufacturing have an average EC of 2.7±0.2 kcal/min. The transportation industry presented relatively moderate estimates of EC (average value 3.2±1.0 kcal/min for male workers) with land transport and postal activities having the highest (average EC: 3.9±0.1 kcal/min) and air transport activities the lowest EC requirements (average EC: 1.8±0.4 kcal/min). Finally, jobs within the tourism industry demonstrated the lowest EC values among

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the five selected industries, with an average EC of 2.5±0.9 kcal/min. The above energy-demanding classification of industries is important since it indicates that the workers' energy cost can vary substantially among different jobs and industries and there is a need for a more specialized approach for each type of work. Occupational health services should take into consideration this variability when promoting methods and tools to protect workers' health and enhance their physical, mental, and social well-being, as well as in preventing ill-health and accidents.

An interesting aspect of the present analysis stems from the time emergence of the identified studies. During the pre-World War II period, the average number of relevant studies published per year was 0.22. The publications/year increased to 0.83 in the period 1946-1975 and then declined again to 0.56 in the period 1977-2007, only to rise to 0.9 during the past 10 years. This appears consistent with the history of the global economic growth during the 20th and 21st centuries[75)] and, thus, the need to assess workers' health, performance, and productivity. Indeed, the first decades of the 20th century was characterized by rapid technological change but also by economic instability and crisis[75)]. By the late 1930s, recovery was underway, but industrial production was, once again, disrupted due to World War II[75)]. The period 1946-1975, was a time of rapid change and economic growth which[76)] was followed by a period of economic/industrial slowdown and then, from the mid-1990s, the era of the "New Economy"[77)]. Therefore, it seems logical to postulate that the intensification of economic/industrial growth in the mid-twentieth century generated the need to measure human EC with the aim of improving workers' efficiency, health, and safety. Nevertheless, it is important to note that the physical demands of many jobs in the studied industries have changed markedly since those times. Therefore, an update of the EC estimates in these occupations is needed, especially since several guidelines and standards are using this knowledge.

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During the past 10 years, a renewal of interest regarding occupational EC has been observed which is fuelled by technological developments in wireless communication and miniaturized sensors. Another potential source for the renewed interest in this research field may stem from a shift in the load that workers are expected to perform today due to globalization in combination with national objectives for competitiveness and economic growth[78]. As a result, several health-related issues have emerged in occupational settings, such as burn-out syndrome[4] and work exhaustion[3], that need to be considered. In addition, one of the most immediate and obvious effects of climate change is the increase in environmental temperatures and workers are already affected since many workplaces are becoming very hot[79, 5]. Heat stress in occupational settings leads to reduced labour effort and productivity loss with detrimental effects on economic growth[80]. Therefore, an updated analysis looking for an optimal compromise between workers' physiological capacity and the demands of the job, in combination with indoor/outdoor environmental conditions, is urgently needed. The EC estimation of an extensive range of different occupational settings is a necessary component in health and safety calculations/assessments according to guidelines aiming to preserve workers' health and wellbeing.

Despite our best intentions, it is important to note that the EC estimates provided in this paper should be considered through the prism of certain limitations. For instance, while some studies (e.g., Bielski,1976[69], Brun,1979[30], and Abdelhamid, 2002[40]) provide a comprehensive description of several tasks included in each job, other papers (e.g., Inoue, 1955[65], Davies, 1976[29], and Moharana, 2013[64]) provide only a single-phrase description or a job title. While we addressed the fact that the number of workers assessed in each study were different, by weighing the EC estimates provided for each NACE code, it is important to note that most of the studies assessed few or no women workers. As a consequence, we were only able to report EC estimates for women workers in 16 out of the 35 (45.7%) jobs studied. We attempted to assess

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the quality of the different studies and to weigh their effects against each other based on their quality, the 95% confidence intervals provided, and the heterogeneity of the data (e.g., by using the I^2 statistic, funnel plots, and the software such as RevMan). Unfortunately, this was not possible because the vast majority of job tasks in the analyzed studies were assessed by only one or two studies for each sex. Even when this was not true, the participants, methods to assess EC, and precise job descriptions varied considerably between studies. For instance, as shown in eTables 1a-c, the job task "weeding" has been reported by Benedict[22)] during gardening, by Kahn[25)] during cereal farming, by Edholm[34)] during vineyard farming/viticulture, by Brun[32)] during cotton farming, by de Guzman[60)] during rice farming, as well as Costa[33)] during apple farming. It becomes evident that, even in this case – where several studies assessed the same job task – a forest plot weighing the different studies would be inappropriate. Finally, all studies included in this review have been conducted in field settings/workplaces and, thus, it is logical to assume workers have been assessed while wearing normal work uniform. However, it is important to mention that the provided EC values may underestimate the true EC by 2.4-20.9% when added (i.e., more than that worn in typical workplaces) protective clothing is worn[81)].

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CONCLUSION

In this paper we provide a detailed list of EC estimates in jobs within five major industries: (i) tourism (i.e., accommodation and food services), (ii) agriculture, (iii) construction, (iv) manufacturing, and (v) transportation. It is hoped that this information will aid the development of future instruments and guidelines aiming to protect workers' health, safety, and productivity by, for instance, helping to determine the tolerance limits for daily energy expenditure during the working hours. Future research should provide updated EC estimates in these jobs within a wide spectrum of occupational settings taking into account the sex, age, and physiological characteristics of the workers as well as the individual characteristics of each workplace. Assessing and quantifying the physical demands associated for each job task within an industry is key to fully understanding the requirements of working safely and without risks.

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Table 1. Job types in each industry, workers studied, and EC assessment method in all studies included in this review.

Industry	Study	Job type	Workers	EC assessment method
Tourism	Moharana, 2013[64]	Hotel (kitchen, housekeeping, laundry)	78 *	Heart rate monitoring
	Wills, 2016[74]	Restaurant work	5 ♂ / 15 ♀	Time motion analysis
Agriculture	Benedict, 1909[22]	Gardening	3 ♂	Indirect calorimetry
	Farkas, 1932[23]	Cereal farming	15 ♂	Indirect calorimetry
	Kahn, 1933[25]	Cereal farming	4 ♂ / 5 ♀	Indirect calorimetry
	Glaser, 1952[26]	Lumberjack	1 ♂	Indirect calorimetry
	Hettinger, 1953[27]	Cow milking	1 ♂	Time motion analysis
	Hettinger, 1953[27]	Ploughing	7 ♂	Indirect calorimetry
	Philips, 1954[28]	Gardening	7 ♂	Indirect calorimetry
	Edholm, 1973[34]	Vineyard farming / Viticulture	39♂ / 6 ♀	Indirect calorimetry
	Davies, 1976[29]	Sugar cane farming	42 ♂	Indirect calorimetry
	Brun,1979[30]	Cotton farming	45 ♂	Indirect calorimetry
	Nag, 1980[31]	Seeding	5 ♂	Indirect calorimetry
	Brun,1981[32]	General farming	30 ♂	Indirect calorimetry
	de Guzman, 1984[35]	Rice farming	10 ♂ / 10♀	Indirect calorimetry
	Brun, 1992[24]	General farming	132♀	Indirect calorimetry
	Costa, 1989[33]	Apple farming	17 ♂	Indirect calorimetry
	Ioannou, 2017[5]	Grape-picking	4 ♂ / 2 ♀	Time motion analysis
Construction	Baader, 1929[36]	General construction	1 ♂	Indirect calorimetry
	Müller, 1958[37]	Earthworks	2 ♂	Indirect calorimetry
	Ilmarinen, 1980[38]	General construction	21 ♂	Indirect calorimetry
	Almero, 1984[39]	General construction	25 ♂	Indirect calorimetry
	Abdelhamid, 2002[40]	General construction	18 ♂	Indirect calorimetry
Manufacturing	Greenwood, 1919[47]	Munition industry	52 ♀	Indirect calorimetry
	Kagan, 1928[50]	Machinery assembly	9 ♂	Indirect calorimetry
	Farkas, 1932[23]	Tailor industry	2 ♂	Indirect calorimetry
	Lehman, 1950[43]	Leather industry	10 ♂	Indirect calorimetry
	Lehman, 1950[43]	Printing industry	4 ♂	Indirect calorimetry
	Lehman, 1950[43]	Press goods industry	6 ♂	Indirect calorimetry
	Inoue, 1955[65]	Paper industry	6 ♂	Heart rate monitoring
	Turner, 1955[45]	Plastic and ebonite moulding	158 ♂	Indirect calorimetry
	Ford,1958[68]	Metal industry	26 ♂	Heart rate monitoring
	Raven, 1973[46]	Aluminium smelting industry	8 ♂	Indirect calorimetry
	Bielski,1976[69]	Furniture industry	10 ♂	Heart rate monitoring
	Aunola,1979[49]	Machine and tool manufacturing	190 ♂ / 47 ♀	Indirect calorimetry
	Vankhanen, 1978[44]	Coke industry	57 *	Indirect calorimetry
	de Guzman, 1979[42]	Textile industry	25 ♂ / 14 ♀	Indirect calorimetry
	Kerimova,1987[51]	Oil wells repairing	3 ♂	Indirect calorimetry
	Bortkiewicz, 2006[41]	Food industry	18 ♂ / 26 ♀	Indirect calorimetry
	Dowell, 2009[66]	Glass industry	18 ♂	Heart rate monitoring
	Biswas, 2012[67]	Aluminium industry	17 ♂	Heart rate monitoring
	Kalantary, 2015[70]	Automotive industry	42 ♂	Heart rate monitoring
	De la Riva, 2016[71]	Automotive industry	32 ♂ / 23 ♀	Heart rate monitoring
	Durnin, 1967[82]	Wood industry	ND	ND
	Durnin, 1967[82]	Chemical industry	ND	ND
	Bliss, 1964[48]	Electrical industry	36 ♂	Indirect calorimetry
Transportation	Benedict, 1909[22]	Car driving	3 ♂	Indirect calorimetry
	Benedict, 1909[22]	Motorcycle driving	3 ♂	Indirect calorimetry
	Crowden, 1941[63]	Postal work	4 ♂	Indirect calorimetry
	Karpovich, 1946[53]	Aircraft piloting	27 ♂	Indirect calorimetry
	Corey, 1948[54]	Aircraft piloting	10 ♂	Indirect calorimetry
	Lehman, 1959[61]	Transportation equipment cleaning	7 ♀	Indirect calorimetry
	Das,1966[58]	Load carrying	6 ♂	Indirect calorimetry

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Littell,1969[55)]	Aircraft piloting	16 ♂	Indirect calorimetry
Rohmert, 1974[62)]	Postal work	34 ♂	Indirect calorimetry
Malhotra,1976[52)]	Submarine sailing	24 ♂	Indirect calorimetry
de Guzman et al,1978[60)]	Office work	10 ♂ / 10 ♀	Indirect calorimetry
Samanta,1987[59)]	Load carrying	5 ♂	Indirect calorimetry
Thornton,1984[56)]	Aicraft piloting	12 ♂	Indirect calorimetry
Theurel, 2008[72)]	Postal work	14 ♂	Heart rate monitoring
Pradhan, 2017[73)]	Bus driving	48 ♂	Heart rate monitoring

Note: * = the sex distribution information is not provided. Moharana, 2013[64)] were contacted but did not reply to queries.
Key: EC = energy cost; ♂ = males; ♀ = females; ND = no data provided.

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Table 2. Estimated energy cost for each NACE description across the five industries.

Industry	NACE code	NACE description	Energy cost: kcal/min	Energy cost: Watts[1]
Tourism	I55	Accommodation	3.132±0.269 (♂♀)	218(♂♀)
	I56	Food and beverage service activities	1.916±0.630 (♂♀)	134 (♂♀)
Agriculture	A	Agriculture, forestry and fishing	6.022±2.52 (♂) / 2.879±1.01 (♀)	420 (♂) / 200 (♀)
Construction	F41-F43	Construction of buildings, civil engineering, specialised construction activities	4.950±1.58 (♂)	345 (♂)
Manufacturing	C10-C12	Manufacture of food products, beverages & tobacco products	3.020 (♂) / 2.030 (♀)[2]	210 (♂) / 142 (♀)[2]
	C13-C14	Manufacture of textiles and wearing apparel	2.903±0.60 (♂) / 1.743±0.54 (♀)	202(♂) / 122(♀)
	C15	Manufacture of leather and related products	2.850±0.21 (♂)	200 (♂)
	C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	4.130±0.68 (♂)	288 (♂)
	C17	Manufacture of paper and paper products	5.420±1.24 (♂)	378 (♂)
	C18	Printing and reproduction of recorded media	2.90±1.06 (♂)	202 (♂)
	C19	Manufacture of coke and refined petroleum products	6.35 (♂) / 5.52 (♀)[3]	443 (♂) / 385 (♀)[3]
	C20-C21	Manufacture of chemicals and chemical products and basic pharmaceutical products	4.86±1.25 (♂)	339 (♂)
	C22	Manufacture of rubber and plastic products	3.92±1.05 (♂)	273 (♂)
	C23	Manufacture of other non-metallic mineral products	2.58±2.21 (♂)	180 (♂)
	C24	Manufacture of basic metals	5.052±1.01 (♂)	352 (♂)
	C25	Manufacture of fabricated metal products, except machinery and equipment	2.51±0.90 (♂) / 3.59±0.76 (♀)	175 (♂) / 250 (♀)
	C26-C27	Manufacture of computer, electronic and optical products and electrical equipment	3.65±0.87 (♂)	255 (♂)
	C28	Manufacture of machinery and equipment	3.263±0.86 (♂) / 2.20±0.82 (♀)	228 (♂) / 153 (♀)
	C29-C30	Manufacture of motor vehicles, trailers & semi-trailers and other transport equipment	3.367±0.73 (♂) / 2.82±0.67 (♀)	235 (♂) / 197 (♀)
	C31	Manufacture of furniture	3.090 (♂)[4]	215 (♂)[4]
	C32	Other manufacturing	3.809±1.09 (♂) / 3.029±1.25 (♀)	266 (♂) / 211(♀)
	C33	Repair and installation of machinery & equipment	4.900±1.76 (♂)	342 (♂)
Transportation	H49	Land transport and transport via pipelines	3.811±0.55 (♂)	266 (♂)
	H50	Water transport	2.550±1.54 (♂)	178 (♂)
	H51	Air transport	1.847±0.40 (♂)	129 (♂)
	H52	Warehousing and support activities for transportation	3.619 ±2.27 (♂) / 2.367 ±1.66 (♀)	252 (♂) / 165 (♀)
	H53	Postal and courier activities	4.107 ±0.40 (♂)	286 (♂)

Note: [1] = kcal/min was converted into Watt using the formula 1 kcal/min = 69.78 Watts.
[2] = original results presented as range [(♂:2.50-3.54, ♀:1.56-2.50, kcal/min) (♂:174-247, ♀:109-174, Watts)];
[3] = original results presented as range [(♂:5.21-7.50, ♀:4.58-6.45, kcal/min) (♂:363-523, ♀:319-450, Watts)];
[4] = original results presented as range (♂:2.14-4.03, kcal/min; ♂:149-281, Watts).
Key: NACE = statistical classification of economic activities in the European Community (*Nomenclature statistique des activités économiques dans la Communauté Européenne*); ♂ = males; ♀ = females; ♂♀ = values apply to both males and females.

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Figure 1. Rectal temperature and fluid loss using the Predicted Heat Strain model for an individual performing light (e.g., light polishing; 207 Watts; grey line) or heavier (e.g., drilling; 476 W; black line) work with a hand tool for 8 hours while wearing typical work uniform with long sleeves in a thermoneutral (26°C air and radiant temperatures; 40% relative humidity) indoor (air velocity: 0.3 m/sec) environment.

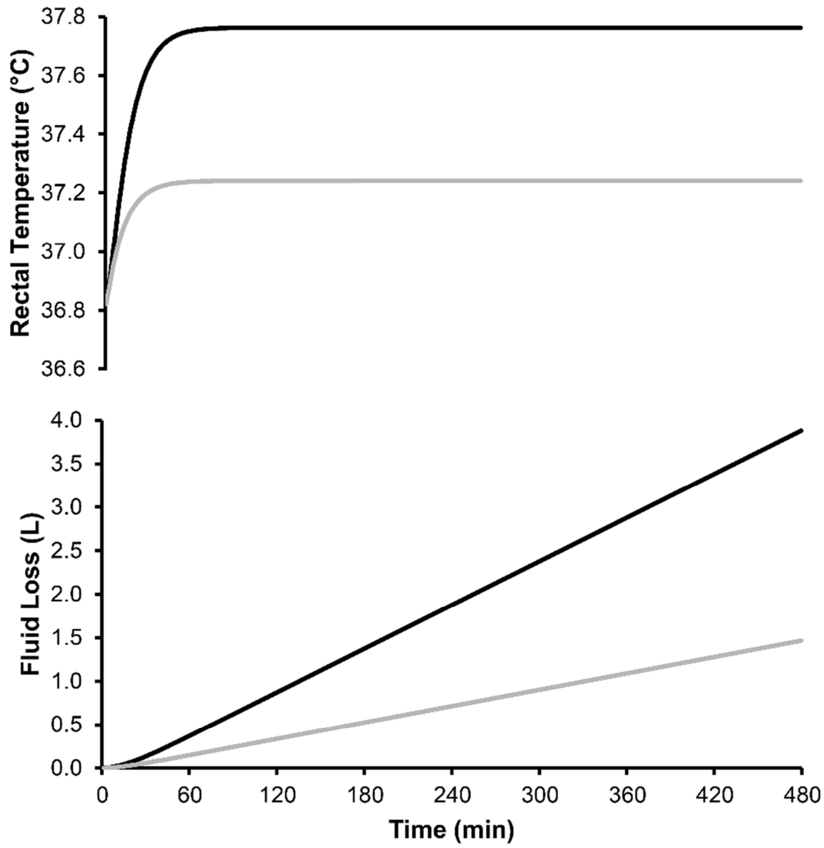

Figure 2. Chronological distribution of all the studies included in this review.

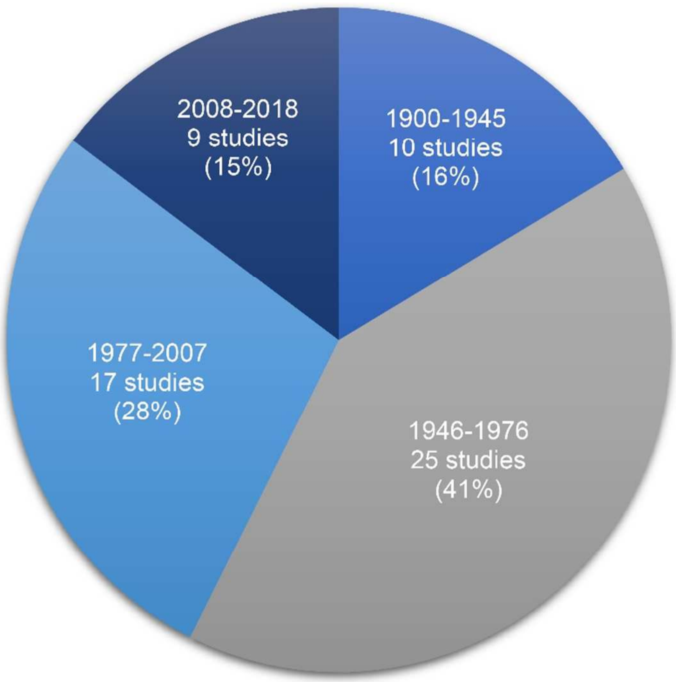

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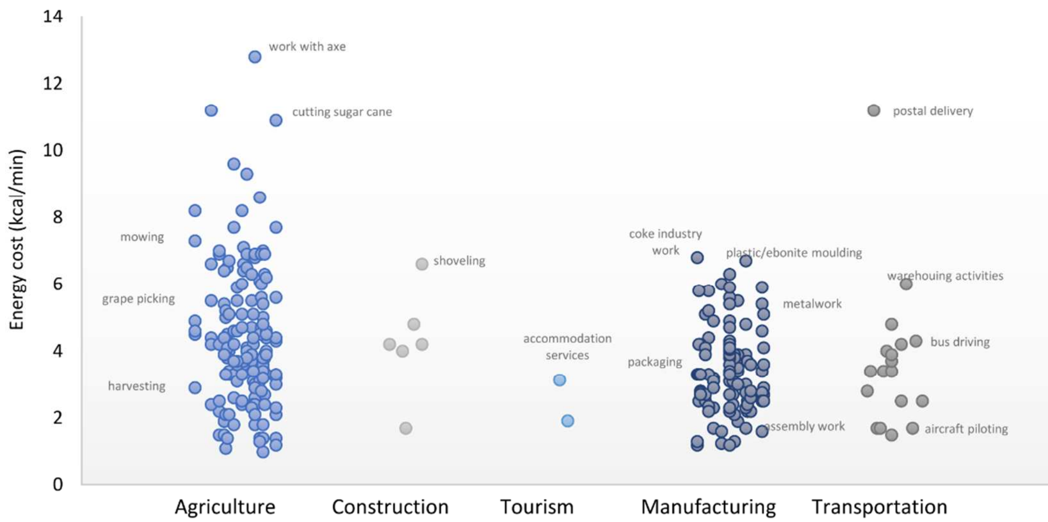
Figure 3. Average energy cost for each of the 325 tasks in the five selected industries which have been assessed in the 61 studied included in this analysis.



Review

Metabolic energy cost of workers in agriculture, construction, manufacturing, tourism, and transportation industries

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Running title: WORKER ENERGY COST IN FIVE MAJOR INDUSTRIES

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The aim of this study was to to review the existing literature and provide a detailed list of EC estimations in jobs/tasks included in five selected industries such as (i) accommodation and food services, (ii) agriculture, (iii) construction, (iv) manufacturing, and (v) transportation. This is important because the aforementioned five industries have a major impact in the global economy. For instance, together they represent 40% of the European Union's GDP and 50% of its workforce. A total of 63 studies were identified and 1667 workers were evaluated while performing a large number of tasks related to each one of the five selected industries. The averaged values for each NACE code (i.e., *Nomenclature statistique des activités économiques dans la Communauté européenne*; statistical classification of economic activities in the European Community)[1] appear in the main part of the manuscript. The energy cost data from all studies included in this review regarding each individual task type appear in the following tables. Details about the estimation of EC for each NACE code are provided below.

Tourism (i.e., Accommodation and food services activities) (I)

This sector is divided into 2 NACE codes [Accommodation (I55); Food services (I56)] corresponding to the job types assessed in two studies[2, 3] which monitored a total of 98 workers.

Accommodation (I55)

Moharana *et al.*[2] assessed the EC of 78 male and female hotel employees working in the kitchen, housekeeping, and laundry departments of a 3-star hotel using heart rate monitoring.

Food and beverage service activities (I56)

Wills *et al.*[3] monitored 5 male and 15 female servers during normal job duties in three different restaurants and estimated EC using time motion analysis.

Agriculture (A)

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The tasks included in this NACE code correspond to the job types assessed in 16 studies[4-18] which monitored a total of 230 male and 155 female workers. The EC is reported for many tasks including weeding, mowing wheat, ploughing and threshing[4, 5, 18, 6], working with axe, milking by hand/machine, ploughing, grass cutting, hoeing, load carrying, cutting cane, cotton harvesting, tending animals, seeding, spraying and mowing[7-14, 18], tractor driving, potato/orange picking, weeding, seeding, forking grass, harvesting, planting shoveling, plowing and spraying[15, 16], as well as grape-picking[17]. The EC data of all the aforementioned tasks appear in an Appendix and were averaged to provide a single sex-specific EC for this NACE code (Table 2 in main text).

Construction (F)

This sector is divided into 3 NACE codes [Construction of buildings (F41); Civil engineering (F42); Specialized construction activities (F43)] corresponding to the job types assessed in 5 studies[19-23] which monitored a total of 67 male workers. The EC is reported for many tasks including transporting concrete, cleaning up, removing panels, carrying, placing concrete, brick layering, loader operating, scaffolding, load carrying, mixing cement using shovel, tapping-chipping cement walls, shoveling sand, painting, and performing other miscellaneous earthworks[19-23]. The EC data of all the aforementioned tasks appear in an Appendix. Given that the physical characteristics of job types included in the three NACE codes were overlapping, the data from all five studies were merged to provide a single EC for the NACE codes F41-F43 (Table 2 in main text).

Manufacturing (C)

This sector is divided into 24 NACE codes (C10-C33) corresponding to the job types assessed in 23 studies[24-31, 5, 32-42] which monitored a total of 839 male and female

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workers. The EC data of all the relevant tasks appear in an Appendix. Given that the physical characteristics of job types included in some NACE codes were overlapping, the data from all studies assessing EC in these jobs were merged to provide a single EC (Table 2 in main text).

(i) Manufacture of food products (C10) / Manufacture of beverages (C11) / Manufacture of tobacco products (C12)

Bortkiewicz *et al.*[27)] used indirect calorimetry to assess the EC of 44 workers from different departments of a foodstuff industry (Table 2 in main text).

(ii) Manufacture of textiles (C13) / Manufacture of wearing apparel (C14) / Manufacture of leather and related products (C15)

The EC of 51 workers is reported for several tasks in textile manufacturing including textile cutting, machine sewing, hand sewing and pressing[5)], cloth cutting and inspecting, dyeing, washing-padding, weaving, creeling, counting yarns, warping, delivering and collecting boxes, spinning, walking[28)], leather shoe manufacturing and repairing[43)]. The data from all tasks were merged to provide a single EC (Table 2 in main text).

(iii) Manufacture of wearing of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials (C16)

Durnin and Passmore[31)] report the EC of workers for several tasks in wood manufacturing including carpenter assembling and finishing, cabinet maker, laminating machine operator, milling machine operator, sanding machine operator, spray painter, wood stainer and packaging. The data from all tasks were merged to provide a single EC (Table 2 in main text).

(iv) Manufacture of paper and paper products (C17)

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Inoue *et al.*[33)] used heart rate monitoring to assess the EC of six workers for many tasks in the paper industry including carrying paper machine parts, standing for long periods, working with hands above shoulder levels, and repairing a paper machine. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(v) Printing and reproduction of recorded media (C18)

Lehman *et al*.[43)] used indirect calorimetry to assess the EC of 10 workers for several tasks in the printing and press good industries including handmade book composition, printing, paper layering, and book binding. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(vi) Manufacture of coke and refined petroleum products (C19)

Vankhanen *et al*.[41)] used indirect calorimetry to assess the EC of 57 workers across the main departments of a coke-chemical plant (Table 2 in main text).

(vii) Manufacture of chemicals and chemical products (C20) / Manufacture of basic pharmaceutical products and pharmaceutical preparations (C21)

Durnin and Passmore[31)] report the EC of workers for several tasks in the chemical industry including machine operation, oil refining, semi-skilled work, dispatch grinding, stirring machine operating, and stock room work. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(viii) Manufacture of rubber and plastic products (C22)

Turner *et al.*[39)] used indirect calorimetry to assess the EC of 158 workers for several tasks in a plastic and ebonite industrial plant, including loading chemicals into a mixer, ebonite moulding, ebonite and plastic finishing, machine fitting, and cutting battery plates. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

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(ix) Manufacture of other non-metallic mineral products (C23)

Dowell *et al*.[30] used heart rate monitoring to assess the EC of 18 workers for several tasks in a glass manufacturing plant including manual work, work with one arm, work with both arms, and whole-body work. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(x) Manufacture of basic metals (C24)

The tasks included in this NACE code were assessed in two studies[38, 25] which monitored a total of 25 workers in the aluminium industry. The EC is reported for many tasks including crowbar/hammer work, handling metal, recovering molten metal[38] and cast box preparation, sand handling, metal handling, furnace operation and product finishing[25]. The EC data of all the aforementioned tasks appear in an Appendix and were averaged to provide a single EC estimate for this NACE code (Table 2 in main text).

(xi) Manufacture of fabricated metal products, except machinery and equipment (C25)

The tasks included in this NACE code were assessed in two studies[32, 40] which monitored a total of 78 workers in the munition and metal product industries. The EC is reported for many tasks including forging, stamping, tool setting, finishing copper bands, carrying loads, cleaning, drying[32] and metal product manufacturing[40]. The EC data of all the aforementioned tasks appear in an Appendix and were averaged to provide a single EC estimate for this NACE code (Table 2 in main text).

(xii) Manufacture of computer, electronic and optical products (C26) / Manufacture of electrical equipment (C27)

Bliss *et al.*[26] used indirect calorimetry to assess the EC of 36 workers for a variety of tasks in an electrical plant including armature winding, coil assembly, galvanizing,

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rolling machine operator, stock room work, and trimming. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(xiii) Manufacture of machinery and equipment n.e.c. (C28)

Aunola *et al.*[24)] used indirect calorimetry to assess the EC of 237 workers for several tasks in the machinery and equipment industries including forging, welding, surface finishing, machine working and installation, assembly and inspection, storage and maintenance, as well as technical, sales, and office work. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(xiv) Manufacture of motor vehicles, trailers and semi-trailers / C30. Manufacture of other transport equipment (C29)

The tasks included in this NACE code were assessed in two studies[29, 35)] which monitored a total of 97 workers in the automotive industry. The EC is reported for many tasks including heavy pressing, manual pressing, metalworking, and administration work[35)] as well as cable cutting, pressing, manual assembly, assembly on board, taping operation, electrical testing, quality inspection, and material handling[29)]. The EC data of all the aforementioned tasks appear in an Appendix and were averaged to provide a single EC estimate for this NACE code (Table 2 in main text).

(xv) Manufacture of furniture (C31)

Bielski *et al.*[42)] used heart rate monitoring to assess the EC of 10 workers for several tasks in a furniture manufacturing plant, including sizing saw, cross cut saw, oscillating single spindle mortising machine, spindle moulder, thickness planer, and edge gluing press chain. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(xvi) Other manufacturing (C32)

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The average of all EC values reported across the 23 NACE codes (C10-C33) in the manufacturing industry was used as an estimate for this NACE code.

(xvii) Repair and installation of machinery and equipment (C33)

Kagan *et al.*[34)] used indirect calorimetry to assess the EC of nine workers for several tasks in an machinery assembly plant including working entirely by hand and when machines were put together on a conveyor system. Kerimova *et al* [36)], used indirect calorimetry to assess the EC of three workers in the oils wells repairing industry. The EC data of all the aforementioned tasks appear in an Appendix and were averaged to provide a single EC estimate for this NACE code (Table 2 in main text).

Transportation (H)

This sector is divided into five NACE codes [Land transport and transport via pipelines (H49); Water transport (H50); Air transport (H51); Warehousing and support activities for transportation (H52), as well as Postal and courier activities (H53)] corresponding to the job types assessed in 15 studies whichmonitored a total of 216 male and 17 female workers. The EC data of all the tasks for each job type appear in an Appendix.

(i) *Land transport and transport via pipelines (H49)*

The tasks included in this NACE code were assessed in two studies[4, 44)] which monitored a total of 54 workers in land transportation. The EC is reported for many tasks including car, motorcycle, and bus driving[4, 44)]. The EC data of all the aforementioned tasks appear in an Appendix and were averaged to provide a single EC estimate for this NACE code (Table 2 in main text).

(ii) Water transport (H50)

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Malhotra *et al.*[45], used indirect calorimetry to assess the EC of 24 workers for several tasks in submarine sailing including resting, reading/writing, standing, eating/drinking, equipment operation, action station, watch keeping, equipment cleaning, ascending and descending ladders, walking between compartments, loading and unloading, as well as ship cleaning. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(iii) Air transport (H51)

The tasks included in this NACE code were assessed in four studies[46-49] which used indirect calorimetry to evaluate a total of 65 workers during aircraft piloting. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

(iv) Warehousing and support activities for transportation (H52)

This sector includes job types such as operating of transport infrastructure (e.g. airports, harbours, tunnels, bridges, etc.), activities of transport agencies and cargo handling[50]. The EC of 38 workers is reported for several tasks in warehousing and support activities and transportation industries including carrying load and manual lifting of loads[51, 52], office working[53] and cleaning transport facilities[37]. The data from all task were merged to provide a single EC estimate for this NACE code (Table 2 in main text).

(v) Postal and courier activities (H53)

Indirect calorimetry was used to assess the EC of workers in several tasks in postal and courier activities including mail sorting, office work and outside mail distribution[54-56]. The data from all tasks were merged to provide a single EC estimate (Table 2 in main text).

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eTable 1(a). Breakdown of job types, energy cost, and workers' sex in all agriculture studies included in this review.

Agriculture study (job type)	Task type	Energy cost kcal/min	Energy cost Watts[1]	Assessed workers' sex
Benedict, 1909[4)] (gardening)	Gardening, weeding	4.4	307	(♂)
	Gardening, weeding	5.6	390	(♂)
	Gardening, digging	8.6	600	(♂)
Farkas, 1932[5)] (cereal farming)	Mowing wheat	7.7	537	(♂)
	Mowing barley	7.0	488	(♂)
	Setting up stooks	6.6	460	(♂)
	Binding wheat	7.3	509	(♂)
Kahn, 1933[6)] (cereal farming)	Ploughing	6.9	481	(♂)
	Ploughing	5.4	376	(♂)
	Thrashing rye	5.0	349	(♂)
	Thrashing rye	4.5	314	(♂)
	Binding oats	3.3	230	(♀)
	Binding oats	4.1	286	(♀)
	Binding rye	4.2	293	(♀)
	Binding rye	4.7	327	(♀)
	Weeding rape	3.3	230	(♀)
Glaser, 1952[7)] (lumberjack)	Working with axe	12.8	890	(♂)
Hettinger, 1953[8)] (cow milking)	Milking by hand	4.7	327	(♂)
	Machine milking 1 pail	3.4	237	(♂)
	Machine milking 2 pails	3.9	272	(♂)
	Cleaning milk pails	4.4	307	(♂)
Hettinger, 1953[8)] (ploughing)	Horseploughing	5.9	411	(♂)
	Horseploughing	5.1	355	(♂)
	Tractor ploughing	4.2	293	(♂)
	Tractor ploughing	4.2	293	(♂)
Philips, 1954[9)] (gardening)	Grass cutting	4.3	300	(♂)
	Bush clearing	6.1	425	(♂)
	Hoeing	4.4	307	(♂)
	Head planning, load 20 kg	3.5	244	(♂)
	Log carrying	3.4	237	(♂)
	Tree felling	8.2	572	(♂)
Edholm, 1973[15)] (vineyard farming / viticulture)	Tractor driving	2.2	153	(♂)
	Truck driving	1.9	132	(♂)
	Horse-cart driving	2.1	146	(♂)
	Potato picking	6.5	453	(♂)
	Potato, filling sacks on truck	3.4	237	(♂)
	Potato, load sacks on truck	9.3	649	(♂)
	Potato grading	3.1	216	(♂)
	Orange picking	3.7	258	(♂)
	Weeding	3.0	209	(♂)
	Carrots, picking	2.6	181	(♂)
	Seed casting	4.5	314	(♂)
	Spray insecticide	5.0	349	(♂)
	Manure spreading	6.3	439	(♂)
	Prune vines	4.0	279	(♂)
	Scythe grass	5.9	411	(♂)
	Fork grass	6.0	418	(♂)
	Irrigation pipes, move	7.7	537	(♂)
	Weeding	3.3	230	(♀)
	Scything	11.2	781	(♀)
	Top carrots	2.1	146	(♀)
	Fork grass	4.5	314	(♀)
Davies, 1976[10)] (sugar cane farming)	Cutting sugar cane	10.9	761	(♂)

Note: [1] = kcal/min was converted into Watts using the formula 1kcal/min = 69.78 Watts.

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eTable 1(b). Breakdown of job types, energy cost, and workers' sex in all agriculture studies included in this review.

Agriculture study (job type)	Task type	Energy cost kcal/min	Energy cost Watts[1]	Assessed workers' sex
Brun,1979[11)] (cotton farming)	Picking cotton and carrying sack	3.6	251	(♂)
	Loading, collecting sacks on lorry	7.1	495	(♂)
	Opening/closing irrigation channels	4.5	314	(♂)
	Channel digging	7.0	488	(♂)
	Digging	6.4	446	(♂)
	Weeding	5.2	362	(♂)
	Tending threshing machine	3.8	265	(♂)
	Lifting grain sacks	4.0	279	(♂)
	Winnowing	4.0	279	(♂)
	Tending animals	5.1	355	(♂)
	Collecting and spreading manure	5.5	383	(♂)
	Loading manure	6.8	474	(♂)
	Riding donkey/tractor	2.9	202	(♂)
	Cycling on level dirt road	5.6	390	(♂)
Nag, 1980[12)] (seeding)	Sitting, resting	1.0	69	(♂)
	Free walking on plane surface	2.7	188	(♂)
	Free walking on puddle field	3.3	230	(♂)
	Transplanting, bending on puddle field	3.1	216	(♂)
	Germinating seeder	8.2	572	(♂)
	Germinating seeder (IRRI type)	9.6	669	(♂)
	Manual threshing by beating	4.6	320	(♂)
	Pedal threshing	6.6	460	(♂)
	Pedal threshing, helper	3.2	223	(♂)
Brun,1981[13)] (general farming)	Lying	1.4	97	(♂)
	Sitting	1.4	97	(♂)
	Standing	1.4	97	(♂)
	Walking	3.6	251	(♂)
	Walking slowly	2.9	202	(♂)
	Walking fast	4.2	293	(♂)
	Cycling	4.4	307	(♂)
	Sowing	3.9	272	(♂)
	Thinning out and replanting	3.8	265	(♂)
	Hoeing	5.1	355	(♂)
	Land clearing	6.9	481	(♂)
	Sorghum harvest: standing, cutting	2.4	167	(♂)
	Bent forward, uprooting potatoes	3.9	272	(♂)
	Plucking leaves and stems, standing	6.8	265	(♂)
	Kneeling and sorting, sweet potatoes	1.8	125	(♂)
	Cutting straw with a sickle, bent forward	5.6	390	(♂)
	Walking with a sheaf of straw on head	3.4	237	(♂)
	Pulling and breaking into pieces branches	3.8	265	(♂)
	Cutting wood with a machete	4.6	320	(♂)
	Unloading a cart of branches	3.6	251	(♂)
	Vine weaving	2.4	167	(♂)
	Hand weaving sitting on the ground	2.6	181	(♂)
	Hand sewing	1.8	125	(♂)
	Sewing with treadle sewing machine	2.4	167	(♂)
	Clay kneading	3.0	209	(♂)
	Sawing a calabash by hand, bending	3.1	216	(♂)
	Making mud bricks squatting	3.3	230	(♂)
	Standing, making a mud wall	1.8	125	(♂)
	Digging the earth with a pick-axe	6.4	446	(♂)
	Shovelling mud	4.9	341	(♂)

Note: [1] = kcal/min was converted into Watts using the formula 1kcal/min = 69.78 Watts.

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eTable 1(c). Breakdown of job types, energy cost, and workers' sex in all agriculture studies included in this review.

Agriculture study (job type)	Task type	Energy cost kcal/min	Energy cost Watts[1]	Assessed workers' sex
de Guzman, 1984[16) (rice farming)	Sitting	1.5	104	(♂)
	Standing	1.5	104	(♂)
	Walking	3.3	230	(♂)
	Weeding by hand	4.1	286	(♂)
	Mechanical weeding	6.7	467	(♂)
	Pushing hand tractor	6.5	453	(♂)
	Harvesting	4.4	307	(♂)
	Threshing	6.3	439	(♂)
	Winnowing	2.4	167	(♂)
	Plowing	6.9	481	(♂)
	Harrowing	6.9	481	(♂)
	Spray	5.4	376	(♂)
	Measuring harvested palay	6.9	481	(♂)
	Germinating palay	4.5	314	(♂)
	Carrying and stacking palay	5.5	383	(♂)
	Application of fertilizer	3.3	230	(♂)
	Planting	4.2	293	(♂)
	Mowing with a scythe	4.6	320	(♂)
	Carry palay	5.5	383	(♂)
	Sitting	1.2	83	(♀)
	Standing	1.3	90	(♀)
	Walking	2.3	160	(♀)
	Weeding	3.8	265	(♀)
	Harvesting	3.7	270	(♀)
	Threshing	4.6	320	(♀)
	Winnowing	2.5	174	(♀)
	Planting	3.9	272	(♀)
Brun, 1992[18) (general farming)	Sitting inactive	1.1	76	(♀)
	Standing resting	1.4	97	(♀)
	Squatting washing clothes	2.1	146	(♀)
	Standing hoeing	3.8	265	(♀)
	Bending, planting potatoes	3.4	237	(♀)
	Bending harvesting potatoes	2.3	160	(♀)
	Ploughing with buffalo	2.9	202	(♀)
	Standing sowing rice	2.1	146	(♀)
	Bending, transplanting rice	2.8	195	(♀)
	Bending, cutting rice	3.2	223	(♀)
	Squatting, bundling rice	2.4	167	(♀)
	Standing, threshing rice	3.9	272	(♀)
	Walking, carrying 30–35 kg	3.7	258	(♀)
	Walking, tapping rubber	2.5	174	(♀)
Costa, 1989[14) (apple farming)	Apple pruning	4.6	320	(♂)
	Weeding	6.0	418	(♂)
	Hand spray	4.8	334	(♂)
	Mech spray	2.4	167	(♂)
	Mowing	6.2	432	(♂)
	Picking	4.6	320	(♂)
Ioannou, 2017[17) (grape picking)	Grape-picking	4.7	327	(♂)
	Grape-picking	3.7	258	(♀)

Note: [1] = kcal/min was converted into Watts using the formula 1kcal/min = 69.78 Watts.

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eTable 2. Breakdown of job types, energy cost, and workers' sex in all construction studies included in this review

Construction study (job type)	Task type	Energy cost kcal/min	Energy cost Watt[1]	Assessed workers' sex
Baader, 1929[19)] (general construction)	Making a wall with bricks, mortar at normal rates	4.0	279	(♂)
	Miscellaneous earthworks	1.7	118	(♂)
Müller, 1958[20)] (earthworks)	Miscellaneous earthworks	4.8	335	(♂)
Ilmarinen, 1980[21)] (general construction)	Striking/shoveling ground	6.6	460	(♂)
Almero, 1984[22)] (general construction)	General labor, masonry, electricals, painting	4.2	293	(♂)
Abdelhamid, 2002[23)] (general construction)	Transport concrete, cleaning up, placing concrete, removing layout/staking marks, assembling formwork, stacking, haul bricks/blocks, spread cleaning sand	4.2	293	(♂)

Note: [1] = kcal/min was converted into Watts using the formula 1kcal/min = 69.78 Watts.

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eTable 3(a). Breakdown of job types, energy cost, and workers' sex in all manufacture studies included in this review.

Manufacture study (job type)	Task type	Energy cost kcal/min	Energy cost Watts[1]	Assessed workers' sex
Greenwood, 1919[32)] (munition industry)	Laboring	5.1	355	(♀)
	Cleaning and drying	4.9	341	(♀)
	Gauging	4.0	279	(♀)
	Walking and carrying	3.9	272	(♀)
	Finishing copper bands, tool setting	3.4	237	(♀)
	Heavy turning, hoisting shelf with pulley	3.3	230	(♀)
	Stamping	3.2	223	(♀)
	Forging	3.1	216	(♀)
	Turning and finishing	3.0	209	(♀)
	Light turning	2.5	174	(♀)
Kagan, 1928[34)] (machinery assembly)	Working entirely by hand	5.8	404	(♂)
	Machines were put on a conveyor system	2.8	195	(♂)
Farkas, 1932[5)] (tailor industry)	Cutting	2.5	174	(♂)
	Machine sewing	2.7	188	(♂)
	Hand sewing	1.9	132	(♂)
	Pressing	3.9	272	(♂)
Lehman, 1950[43)] (leather industry)	Shoe repairing	2.7	188	(♂)
	Shoe manufacturing	3.0	209	(♂)
Lehman, 1950[43)] (printing industry)	Printing industry: Hand compositor	2.2	153	(♂)
	Printer	2.2	153	(♂)
	Paper layer	2.5	174	(♂)
	Book-binder	2.3	160	(♂)
Lehman, 1950[43)] (press goods industry)	Pressing household utensils	3.8	265	(♂)
Inoue, 1955[33)] (paper industry)	Working with hands above shoulder level, heavy lifting, standing for long periods	5.4	376	(♂)
Turner, 1955[39)] (plastic and ebonite moulding	Unloading battery boxes from oven	6.8	474	(♂)
	Loading chemicals into mixer	6.0	418	(♂)
	Machine moulding battery plates	5.1	355	(♂)
	Casting lead balls in mould	4.8	334	(♂)
	Straightening lead contact bars	4.6	320	(♂)
	Rimming battery plates	4.4	307	(♂)
	Heavy battery plate casting	4.2	293	(♂)
	Machine fitting	4.2	293	(♂)
	Lead rolling on roller mill	3.9	272	(♂)
	Loading plates into charging vat	3.9	272	(♂)
	Moulding ebonite	3.6	251	(♂)
	Light. battery plate casting	3.6	251	(♂)
	Tool room workers	3.9	272	(♂)
	Turners	3.7	258	(♂)
	Joiners	3.6	251	(♂)
	Cutting battery plates	3.3	230	(♂)
	Plastic moulding	3.3	230	(♂)
	Punching battery plates to size	3.3	230	(♂)
	Machinists (engineering)	3.1	216	(♂)
	Sheet metal worker	3.0	209	(♂)
	Joiner trainee	3.0	209	(♂)
	Medium assembly work	2.7	188	(♂)
	Typewriter mechanic trainee	2.1	146	(♂)
Ford,1958[40)] (metal industry)	Metal product manufacturing	2.5	174	(♂)

Note: [1] = kcal/min was converted into Watts using the formula 1kcal/min = 69.78 Watts.

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eTable 3(b). Breakdown of job types, energy cost, and workers' sex in all manufacture studies included in this review.

Manufacture study (job type)	Task type	Energy cost kcal/min	Energy cost Watts[1]	Assessed workers' sex
Raven, 1973[38] (aluminium smelting industry	Using automatic crowbar, break crust with hand jack hammer, remove cover over pots, placing carbon	4.1	286	(♂)
Bielski et al.,1976[42] (furniture industry)	Sawing, belt sanding, machine, drum sander, oscillating mortising machine, spindle moulder, conveyor system, hydraulic press	3.1	216	(♂)
Aunola et al.,1979[24] (machine and tool manufacturing)	Foundry work, forging, welding, surface finishing, machine working, installation, assembly, inspection, storage, office	3.3/2.2	230/153	(♂♀)
Vankhanen, 1978[41] (coke industry)	Coke industry work	6.3/5.5	439/383	(♂♀)
de Guzman, 1979[28] (textile industry)	Sitting	1.2/1.2	83/83	(♂♀)
	Standing	1.3/1.2	90/83	(♂♀)
	Walking	3.2/2.6	223/181	(♂♀)
	Ringframe spinning	2.6/1.9	181/132	(♂♀)
	Conewinding	3.6/1.9	251/132	(♂♀)
	Warping	3.2/1.5	223/104	(♂♀)
	Weaving	3.6/1.9	251/132	(♂♀)
	Delivering and collecting boxes	5.2	362	(♂)
	Pinwinding	3.3	230	(♂)
	Loading of warp beam	5.8	404	(♂)
	Counting yarns per dent	2.4	167	(♂)
	Creeling	3.4	237	(♂)
	Weaving	3.5	244	(♂)
	Cloth cutting	4.1	286	(♂)
	Writing (sitting activity)	1.3	90	(♂)
	Washing-padding	2.4	167	(♂)
	Releasing and dye mixing	2.6	181	(♂)
	Gig dyeing 2	2.7	188	(♂)
	Backtending or high-curing	1.7	118	(♂)
	Cloth inspecting	1.2	83	(♂)
Kerimova,1987[36] (oils wells repairing)	Oils wells repairing	6.7	474	(♂)
Bortkiewicz, 2006[27] (food industry)	Food manufacture process	3.0/2.0	209/139	(♂/♀)
Dowell, 2009[30] (glass industry)	Sitting	0.3	20	(♂)
	Standing	0.6	41	(♂)
	Walking	2.0-3.0	139/209	(♂)
	Manual work	0.7	48	(♂)
	Work, one arm	1.6	111	(♂)
	Work, both arms	2.2	153	(♂)
	Work, whole body	2.7	188	(♂)
Biswas, 2012[25] (aluminium industry)	Cast box preparation, sand handling, metal handling, furnace operation, product finishing	5.5	383	(♂)
Kalantary, 2015[35] (automotive industry)	Heavy pressing, manual pressing, metalworking, administrative work	3.8	365	(♂)
De la Riva, 2016[29] (automotive industry)	Cable cutting, pressing, assembly, taping operation, electrical testing, quality inspection, material handling	2.8	195	(♂♀)
Durnin, 1967[31] (wood industry)	Carpenter -assembling	3.9	272	(♂)
	Carpenter-finishing	2.9	202	(♂)
	Cabinet maker	5.6	390	(♂)
	Laminating machine operator	4.0	279	(♂)
	Milling machine operator	3.8	265	(♂)
	Sanding machine operator	4.3	300	(♂)
	Spray painter	3.9	272	(♂)
	Wood stainer	4.7	327	(♂)

Note: [1] = kcal/min was converted into Watts using the formula 1kcal/min = 69.78 Watts.

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eTable 3(c). Breakdown of job types, energy cost, and workers' sex in all manufacture studies included in this review

Manufacture study (job type)	Task type	Energy cost kcal/min	Energy cost Watts[1]	Assessed workers' sex
Durnin, 1967[31] (chemical industry)	Machine operator-oil refining	3.6	251	(♂)
	Despatch	3.6	251	(♂)
	Grinding	4.9	341	(♂)
	Stirring machine operator	5.9	411	(♂)
	Stock room work	6.3	439	(♂)
Bliss, 1964[26] (electrical industry)	Armature winding	2.2	153	(♂)
	Battery plate casting	3.9	272	(♂)
	Battery plate punching and cutting	3.4	237	(♂)
	Coil assembly	4.0	279	(♂)
	Dipper	5.4	376	(♂)
	Ebonite moulding	3.4	237	(♂)
	Galvanizing	4.7	327	(♂)
	Materials handling	3.3	230	(♂)
	Punch press operator	4.2	293	(♂)
	Relay	2.3	160	(♂)
	Radio mechanics	2.7	188	(♂)
	Rolling machine operator	2.7	188	(♂)
	Stock room work	4.2	293	(♂)
	Trimming	4.2	293	(♂)
	Wire drawing machine operator	4.1	286	(♂)

Note: [1] = kcal/min was converted into Watts using the formula 1kcal/min = 69.78 Watts.

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Table 4. Breakdown of job types, energy cost, and workers' sex in all transportation studies included in this review

Transportation study (job type)	Task type	Energy cost kcal/min	Energy cost Watts[1]	Assessed workers' sex
Benedict, 1909[4] (land transportation)	Driving a car	2.8	195	(♂)
Benedict, 1909[4] (land transportation)	Driving a motor cycle	3.4	237	(♂)
Crowden, 1941[57] (postal work)	Postal delivery, climbing stairs at usual pack	4.0	279	(♂)
Karpovich, 1946[46] (air transportation)	Airplane piloting	1.7	118	(♂)
Corey, 1948[47] (air transportation)	Airplane piloting	1.7	118	(♂)
Lehman, 1959[37] (cleaning transport facilities)	Sweeping inside a tram Washing inside and outside of trams Washing car Sweeping in a hall	3.4 4.0 3.4 4.2	237 279 237 293	(♀) (♀) (♀) (♀)
Das,1966[51] (cargo)	Load carrying 27 kg	6.0	428	(♂)
Littell,1969[48] (air transportation)	Aircraft piloting (light helicopter, utility helicopter, medium helicopter, fixed wing utility helicopter)	1.7	118	(♂)
Rohmert, 1974[54] (postal work)	Distribute letters, recording discard, empty bag, load/undload the bags in the wagon, repack and stow bag in cargo	4.3	300	(♂)
Malhotra,1976[45] (water transportation)	Submarine sailing	2.5	174	(♂)
de Guzman,1978[53] (transportation support activities)	Office work	1.6/1.4	111/97	(♂/♀)
Samanta,1987[52] (warehousing)	Load carrying	4.8	544	(♂)
Thornton,1984[49] (air transportation)	Helicopter piloting	2.5	174	(♂)
Theurel, 2008[55] (postal work)	Postman work	3.7	258	(♂)
Pradhan, 2017[44] (land transportation)	Bus driving	3.9	272	(♂)

Note: [1] = kcal/min was converted into Watts using the formula 1kcal/min = 69.78 Watts.

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