Open Letter from the Scientific Committee for the Nomination of Emeritus Professor Robert Ayres to the Nobel Memorial Prize in Economic Sciences

Motivation and objective

The undersigned are joining a collective nomination of Robert Ayres for the Nobel Memorial Prize in Economic Sciences, officially *the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel*. The arguments for such nomination are presented herewith.

A summary of Ayres's work (until 2013) is contained in the introductory editorial to a special journal issue in homage to Ayres, entitled *Robert Ayres, Ecological Economics and Industrial Ecology* (van den Bergh 2013). It describes Ayres as "unique, a walking encyclopaedia, an environmental scientist who moves easily between physics, chemistry, biology, economics and engineering, a technological expert and optimist, and an environmental as well as ecological economist" and Ayres's main preoccupation since the 1960s as "how to realize the sustainability transition."

Robert Ayres is widely regarded as one of the intellectual forerunners of *Ecological Economics,* a field that closely connects the environmental sciences with economics and the social sciences more broadly. This group of heterodox economists also include Kenneth Boulding, Herman Daly and Nicholas Georgescu-Roegen. Of this group, Robert Ayres and Herman Daly are the only surviving members. They are rapidly approaching their nineties but are both still active. John Manoochehri has dedicated a two-part episode to Ayres and Daly in his recent series on Apple Podcasts, *Resource Talks* (Manoochehri, 2021). The series investigates such topics as the environmental sciences, sustainable design, nature, and life support systems of the planet including climate. Manoochehri describes both authors as having "led the contemporary reassessment of technical and material progress by revisiting the foundational science, including thermodynamic limits and quantitative economics, and reasserting the need for social-ethical framing of industrial progress." These podcasts have both intellectual and historical value. We encourage all to tune in.

It is completely warranted to award a joint Nobel Prize to both Ayres and Daly, as they are very complementary in their research focus, with Ayres integrating economics and physics and Daly crossing economics to connect it with the broader social sciences. Both write about environmental limits to growth, Daly covering the full analytical spectrum from ultimate means to ultimate ends, while Ayres focuses on ultimate physical means and consequences, as well as breakthroughs and transformation. A joint award would be a very strong and timely statement. It would also acknowledge that modern economic science has always benefited from a wide range of ideas and inputs that do not yet belong to the mainstream thinking of the field. This particularly holds true in the environmental crisis we are facing currently. The award would act as an important reminder that scientific breakthroughs invariably involve dealing with ambitious integration challenges.

Ayres also connects to another heterodox and mainstream area of research that has not been yet awarded a Nobel prize, namely innovation and technological change studies, where names such as (in random order) Philippe Aghion, Brian Arthur, Giovanni Dosi, Richard Nelson, and Sidney Winter come to mind, amongst others. Ayres's contributions to this area have been varied and can be summarized as undertaking essential tests of consistency of technological solutions with fundamental insights from energy and material physics.

Main Argument

After more than 60 years of multi-disciplinary investigations integrating physics, economics, and ecology to tackle many questions and multiple deep-dive research activities, leading to the writing or editing of 30 books and hundreds of book chapters, reports, and journal articles, the main take-away from Ayres's contribution is the need to understand "energy as work," and not just, as traditional economic theory views it, as a mere (intermediate) commodity, sold on the market at some price.

One of the reasons for which the importance of energy in the economy has been downplayed is the structure of national accounts. These are still inspired by neoclassical growth models where final and intermediate outputs are the result of a production (or transformation) function that has a classic mix of capital and labour as inputs. Hence, returns on outputs yield returns for inputs, and ultimately for labour (in the form of wages and salaries) and for capital (rents, interest, royalties, dividends). Mainstream economic theory considers energy as an intermediate good, produced by an appropriate combination of capital and labour. Energy payments thus appear in national accounts as payments to certain industries, such as oil and gas, or electric power generation. One consequence of this accounting approach is that the energy sector's share of payments in the national accounts is quite small, not more than a few percentages.

Most economists thus infer that energy is not especially productive because capital and labor are credited, in such computations, with almost all the value added in the economy. This perspective misses the fact that "capital" is the product of earlier physical work, and that this work nowadays is mostly work done by machines (including computers) activated by energy, and not muscles, as was the case in the days of Adam Smith. The fact that energy carriers (food, fuels, electricity) are still very cheap is the source of our sustainability problem. This value-added view locks economists and policy makers into a mindset that does not allow them to make the conceptual transition that physical energy (and its material equivalents) is a fundamental quantity for the economy – indeed, it is the stuff of the universe – and is neither created nor destroyed by human activity, it is only transformed taking other forms. The correct understanding of energy and its role in the economy and in the biosphere by public and private authorities alike must be central to an effective sustainability transition.

What Ayres proposes for the economic sciences is in the same vein as what Einstein proposed for the physical sciences: *a fundamental relation between energy, materials, and their transformation into goods and services.* The major contribution of Robert Ayres is that energy is a physical input into the entire economy, needed for any kind of work to be done. This fundamental point, which links economics and the physical sciences, has several important consequences which deserve greater acceptance and understanding. In addition, through theoretical and empirical work, Ayres has shown that the role of energy tends to be underplayed and underestimated, leading to major dysfunctions in the economy and hampering the formulation of appropriate energy, resource, and environmental policies.

Energy is present in nature as a gift to the earth itself, or, if we prefer, to humanity if we take an anthropocentric view. This point is important for welfare economics as general equilibrium theory has always left unanswered the question of who initial endowments belong to. The common answer is that individuals own their labour (and hence the returns from their labour), and the same holds for capitalists (even though both are being "taxed" on this ownership to provide adequate returns to the community). The existence of the "common good", energy, radically changes matters in the current debate on the place and rights of the earth in the Anthropocene. For example, quoting van den Bergh (2013), "why do we still tax labour, which is not scarce and just contributes to unemployment, why instead do we not price through taxation things that are scarce, namely energy and material resources?"

Second, productive transformations neither create nor destroy material (first law of thermodynamics), they just transform material into a component applied to getting useful work done (called *exergy*) and a wasteful component (called *anergy).* Energy consists of these two inextricably tied components, anergy being a "dark or grey matter" that complements exergy, the "bright matter." Hence, all useful, low entropy materials that are extracted (from mines, forests, farms, or fisheries) end up sooner or later as useless, high entropy wastes (as stated by the second law of thermodynamics). This disordering process is mirrored by the increase of global entropy that continuously occurs on earth because of industrial production and consumption. Some of these waste products are harmful to life on earth, either because they are toxic (like carbon monoxide or tetra-ethyl lead) or because of undesirable macro-processes (like erosion, ocean acidification, and climate change). The unavoidable consequence of the use of energy then is waste (or anergy), which is a "common bad" that is the dual of the common good that is energy. Both need to be effectively managed - and simultaneously so - as one cannot have one without the other.

Ayres work in the 1960s and 70s elaborated this material-physical view on the economy through mass balance models, useful for asking questions about limits to substitution between labour, capital, materials, and energy, for studying limits to growth, and for historical and predictive materials accounting (forerunning the field of industrial metabolism/ ecology). It also shows that waste treatment does not reduce mass of waste but merely changes its form. This work started with his classical article written with A.V. Kneese, published in the *American Economic Review* (Ayres and Kneese 1969) and with his impressive monograph published by Wiley (Ayres 1978), *Resources, environment, and economics: applications of the materials/energy balance principle*. More details on this line of research are provided below. Its relevance for the environment-versus-growth debate is discussed in the prize-winning article Ayres, R.U.," The second law, the fourth law, recycling and limits to growth," *Ecological Economics* 29 (3), 473–483 (1999).

Understanding the fundamental role of energy (in its multiple material forms) in our economies and societies is vital. Conversely, misunderstandings regarding the role of energy have contributed and will continue to contribute to "fueling" (pun intended) the current environmental crisis and hampering the necessary sustainability transition. A greater understanding and integration of the work of Ayres and his followers will support our combat against climate change and contribute to restoring a more balanced life on the planet.

The prevailing biases and misconceptions surrounding energy have serious consequences in terms of our understanding of economic flows, the correctness of prices, of investment and of technology choices. If energy is incorrectly priced, it will likely lead to wrong technological assessments, particularly – as Ayres has argued – that a multiplicity of technological options is available for the world to take.

The 1969 Article that Lays Out the Groundwork

The groundwork for this view of the world was laid by Ayres in a pathbreaking article, co-authored with his senior fellow of the *Resources for the Future* think tank, Allen V. Kneese, published in the *American Economic Review* in 1969, and entitled *Production, Consumption and Externalities*. This paper is cited more than 2500 times in Google Scholar. It made several important points.

First, the products we consume are the outcome of a production process that starts with extraction, refining, forming and distribution of materials. During that sequence most of the extracted materials are converted into process wastes and discarded. Final products, too, largely become waste at the end of their useful life. So industrial societies produce considerable amounts of waste, and the more they produce energy, the more waste they generate.

The article makes a dire prediction: "Under conditions of intensive economic and population development the environmental media which can receive and assimilate residual wastes are not free goods but natural resources of great value with respect to which voluntary exchange cannot operate because of their common property characteristics" (Ayres and Kneese 1969). While some wastes can be used in a beneficial way (e.g., as filler for dikes or walls) or easily and safely be recycled (like animal manure regenerates the soil), some of the wastes are dangerous and must be detoxified or disposed of in a safe manner so that they do not impose costs on third parties. In an ideal market system, toxic wastes should have negative prices to yield an optimal allocation of resources in society. But in the existing economic system, the costs of disposal or the costs of harm done by untreated pollution are paid by people who get no benefit from the production or consumption activities. These costs are, by definition, *externalities*, which can be very large as the examples of climate change or Covid19 attest.

The disposal and management of these wastes are thus public policy and management imperatives. This insight is still very significant given that we have, even after four decades, been unable to implement all the necessary policies to regulate the externalities of pollutive waste and emissions.

The attribution of a Nobel Memorial Prize in Economic Sciences to Robert Ayres would be most timely. Ayres's work (and that of his colleagues and followers) on the underestimated importance of energy for economic growth and development would be a welcome recognition of the necessity for the economic and social sciences to address the formidable challenge posed by climate change, in majority causes by energy-related emissions, in scientifically sounder ways, and more appropriately linked with the physical sciences.

Energy and Economic Efficiency

Economics is often succinctly defined as being concerned with the efficient allocation of resources. At the beginning of his career, Ayres produced several interesting studies shedding new light on these basic questions. An early and fundamental contribution was to demonstrate the huge inefficiencies involved in automobile transport, which he estimated to be around 1.5% when considering that the goal was to move people (Ayres 1975b). A greater recognition of this fact might have led societies to be less enthusiastically embracing oil fuelled automobile transportation, something that has been countered only recently.

A similar piece of empirical work was to look at the efficiency of nuclear power. During the 60's and 70's decades, the pro-nuclear interests around the Atomic Energy Commission (AEC) argued – in documents prepared for the AEC -- that more government investment in nuclear power was needed because of a pending scarcity of oil. The nuclear lobby at the time boasted the efficiency of nuclear power to be around 50%, which was excessively optimistic and intentionally biased about the future of nuclear fusion as a power source.

Ayres was suspicious of the logic. In effect, the nuclear proponents (and most political and industrial leaders) were assuming that energy from fossil fuels was being utilized in the economy at maximum efficiency (in first law terms). Hence, there seemed little or no room for saving energy by increasing "first law" efficiency, as defined by the *American Physical Society*. First law efficiency refers to the ratio of total energy output to energy input and fails to distinguish between useful energy (exergy) and non-useful, unavailable energy (anergy). Second law efficiency is what we now call *exergy efficiency* and is more relevant for economic analysis: it also is usually greatly lower than first law efficiency, a fact that technological lobbies regularly refuse to mention.

Ayres knew (from his earlier automobile study) that the first law efficiency was deceptively high. This meant that the opportunities for efficiency improvements were drastically under-estimated. A more accurate forecast could have led to greater investment in solar and wind technologies – and storage technology – that might have made the transition away from fossil fuels much less painful than it is going to be.

The latest contribution of Ayres in this vein is the study, with Ed Williams and Miriam Heller, of the energy and material use in the production of semiconductor devices (Williams, Ayres, Heller 2002). They demonstrate the surprisingly high inefficiency of the manufacturing process, concluding that a transition to the intensive use of microchip, in its current composition, will endanger a transition to a "greener" economy, rather than facilitate it. The relevance of this work extends to data centres and blockchains.

Looking back, these studies make important points about the economy and about public policy debates. First, they show that basing efficiency predictions on the physical realities of material transformation demonstrate that the economy as a whole produces huge amounts of waste as by-products, and that these are only increasing as energy use intensifies. Second, many studies in the policy debate are alarmingly biased precisely because they are not based on unambiguous scientific facts and theories (such as the first and second laws of thermodynamics). Third, even on the most basic questions of efficiency, the economics profession still has plenty of progress to make, including through better linkages with the physical sciences. For example, Laitner (2013) calculated that 86% of the primary energy used in the United States can be regarded as inefficient and avoidable. Such numbers underline that the potential and need for energy conservation are huge.

Collaborating with Benjamin Warr and others, Ayres did extend his earlier studies of the energy efficiency of the US economy (Ayres, Ayres, and Warr 2003) to the economies of other countries (Warr, Williams, and Ayres 2008) (Warr et al. 2010). This work found that exergy (maximum useful work that energy sources can perform) is crucial for predicting the long-term pattern of US economic growth. Moreover, exergy was able to explain the part of growth that previously was assigned to black-box technological progress rather than production inputs. The meaning of this result is that without accounting for exergy/energy one obtains a grossly incomplete picture of economic production and growth. This important work scales up the importance of materials and energy accounting to the macrolevel.

Industrial Ecology and Materials Accounting

Ayres is considered one of the founding fathers of *Life Cycle Assessment* (LCA), a key methodology in industrial ecology. His material balance approach, called *Material-Process-Product* model (or MPPM) provided a novel and scientifically rigorous way to estimate the residual pollution of industrial processes in firms, cities, or entire countries. His MPPM models were inspired by traditional Linear Programming/Input-Output models, with alternative processing choices for products that could be made from several intermediates using different processes. His classic 1978 monograph with Wiley, entitled *Resources, Environment and Economics: Applications of the Materials/Energy Balance Principle,* developed the basis for this.

In the 1960s there was a lot of discussion in government about measuring pollution in the air and water, mostly using devices superficially like complicated thermometers. The numbers jumped around a lot, depending on time of day, location, and weather conditions. The US Environmental Protection Agency (EPA) was in the process of being conceived and born, as were a variety of environmental action groups such as Greenpeace. Ayres thought that, in some cases, it would be easier to estimate emissions to the environment indirectly, from the differences between known inputs to an industrial process and known outputs. This idea evolved later into a methodology for tracking material inputs, through a chain of industrial process, into finished products. That methodology became the *Materials-Process-Product Model* and is central to what is now called *Life-Cycle Analysis* (LCA) or *Life Cycle Assessment* (Ayres 1974b, 1976a, 1978a, b, 1987, 1993) (Ayres and Norberg-Bohm 1993) (Ayres, Norberg-Bohm, and Ayres 1993) (Ayres and Ayres 2000).

The *mass-balance approach*, as it later became known, was revisited as *industrial metabolism,* then became known as *industrial ecology,* and as *materials accounting*. The mass-balance approach in life cycle analysis was based on the realization that mass and energy are conserved — and not destroyed – in every transformation of physical material. Since the mass of physical materials extracted from the environment is many times larger than the mass of final products produced and consumed, the difference – the residual – is a flow of materials that are returned to the environment in another form. Much of that difference consists of combustion products from industrial processes – such as smoke and ash emitted to the air. The obvious example is the toxic heavy metal from tetra-ethyl lead that was used to increase the octane level of gasoline. Rather than taking air samples from the sides of highways, it made sense to start from counting the tonnage of lead consumed by the gasoline refineries and assume it all ended up in the air, especially along the roadsides. That represented a more accurate approach which would reveal that current measurement techniques were underestimating the pollution.

The most ambitious application of the methodology of mass-balance accounting was a project at CMU, to reconstruct the pollution levels in the Hudson-Raritan Basin. Ayres with students, was able, from historical agricultural and industrial production data and using mass balance and conservation principles, to reconstruct the history of pollution in the Hudson-Raritan basin. The computations were confirmed by fishery data. Doing so he was, with a group of other scientists, able to prove that pollution in the Hudson-Raritan basin was much higher than was measured by road-side physical measurements. These appeared to reveal little pollution presence relative to the more precise estimates using mass balance and conservation principles. Published references to the work include Ayres and Rod (1986), Ayres, Rod, and McMichael (1987), Ayres and Tarr (1990), Ayres, Ayres, and Tarr (1994), Ayres and Ayres (1994), and Ayres (1998b).

Shortly after finishing the Hudson-Raritan study, Ayres took a sabbatical year in 1987. Director Tom Lee invited him to continue the work he had been doing at Carnegie-Mellon University (on robotics, CAD/CAM, CIM) with an international group of experts at his institute, the International Institute for Applied System Analysis (IIASA) in Laxenburg, near Vienna. IIASA also had an active group working on environmental topics. Ayres's interaction with the group was beneficial. He presented his mass-balance work on the Hudson-Raritan Basin to the group which triggered parallel projects on the Danube basin and the Rhine River. It also led to several large multi-disciplinary projects in which he participated in various roles.

As stated by van den Bergh, Ayres figures prominently as one of the fathers of *industrial ecology* (which he initially called "*industrial metabolism*"), a field now taught in some universities dedicated to documenting material transformations and uses. The field has its own journal, *The Journal of Industrial Ecology,* which is owned by Yale University and headquartered at its *Centre for Industrial Ecology* in the *Yale School of the Environment*. The journal publishes sustainability and circular economy research that considers the relationship between the environment and socio-economic systems. Since its inception, Ayres is a member of its Editorial Board.

Several books detail and illustrate this approach and speak volumes (pun intended) for his contribution, including a *Handbook of Industrial Ecology:* Ayres (1978b), Ayres and Simonis (1994), Ayres and Ayres (1996, 1998, 1999, 2002), Ayres and Weaver (1998) all attest to the depth of the contribution and the thoroughness of the methods applied and illustrated. Ayres also extended the mass balance thinking, amongst other applications, to waste mining and the circular economy (Ayres, 1997) (Ayres, Talens Peiro, and Villalba Mendez 2013, 2014).

Technological Dynamics and Forecasting

Robert Ayres has also contributed to the areas of *technological innovation* and *technological forecasting*. As a result of his observations and studies of technological dynamics, Ayres concluded that technological innovation is not a continuous process (as most economists assume), but one of periodic disruption as an old technology, having reached its limits, needs to be replaced (Ayres 1985, 1987, 1988a). This substitution process can be quite chaotic as many candidates compete making the winner-to-be hard to predict.

Yet the socio-economic and environmental consequences of a major technological substitution can be huge, as we are seeing now. A good forecast of the outcome of a technological competition can have a considerable influence on investment. The neglect of Ayres's past work on the inefficiencies of automobile transportation played a part in allowing the combined forces of oil and automobile industries to massively contribute to the environmental disaster we are experiencing today. A greater awareness of the huge inefficiencies in these conversions might have led to different technological trajectories also in this economic sector.

This work was motivated by an extensive study the robotics industry, with his PhD student Steven Miller (Ayres 1984a, 1986) (Ayres and Miller 1983) (Ayres, Miller et al. 1985). Ayres had a problem with the idea of unlimited substitution and hence robotics, with its flexible manufacturing systems, was of interest to him. With Steve Miller, he suggested a new economic growth model in which technological knowledge itself is a factor of production (an assumption also adopted by Paul Romer). Increased knowledge expands the technological efficiency of resource utilization. While knowledge can increase without limit, material substitution possibilities cannot. Hence economic growth is limited by the availability of scarce resources, even if information keeps increasing (Ayres 1988b).

He revisited the model, incorporating more concepts from information theory, to explain the Kondratieff “long wave.” This updated version (Ayres 1990) of the model had two explicit conclusions: 1) economic growth rates are inherently discontinuous; 2) progressive exhaustion or obsolescence of a previously essential resource will trigger the creation of a new technology or a new sector. These fit very well into Schumpeter’s ideas.

The main point, which we already hinted at earlier, is that there is an essential difference between an improvement and a breakthrough. Improvements can make a big difference over time, but improvements run into limits. When they do, a radical change is needed. *It is why technologies have life cycles, like organisms*. The transistor replaced the vacuum tube for electronic switching purposes because the vacuum tube had reached a limit. The internet is not just an improvement on the pony express (or the old postal service). Google search is not just an improvement on the traditional library search. These are the result of major choices which because they differ, bring with them major economic and societal implications.

These differences in technologies are important and make the transitions between eras difficult and chaotic. Technological change and economic growth are therefore not smooth and gradual processes. Technological change creates new assets and wipes out traditional assets (such as asbestos insulation or underground petroleum resources, for one instance). When that happens, wealth is destroyed, and growth may be temporarily negative. To sum up, technological change is discontinuous and makes economic growth neither continuous nor smooth. It is why Ayres called it the “barrier-breakthrough” process. Every breakthrough starts from a barrier. This model is qualitatively consistent with the well-known “S-shaped curve” phenomenon, describing measures of technological performance over time (Ayres 2006). The model is also qualitatively consistent with Schumpeter's explanation of the so-called Kondratieff or “long” wave.

Mainstream economic theory still assumes that technological change is a gradual and steady function of time. For that reason, economists could not predict any of the great changes that occurred, from steam power to electric power, to plastics, radio, TV, mass produced automobiles and aircraft.

A partial list of Ayres’s relevant papers on technological change, including those mentioned above and mostly written during his period at IIASA, are: (Ayres 1975a, 1984b, 1985, 1988a, 1989a, 1991, 1994, 2006) (Ayres and Ezekoye 1991) (Ayres and Zuscovitch 1990) (Vasko, Ayres, and Fontvieille 1990).

The shift that Ayres made in economic growth theory was to move away from abstract economic reasoning to one that deals with specific material aspects of economic growth and technological change made. It convinced him that economic growth cannot be treated as a simple process of accumulation of only abstract aggregates like labour, capital, and knowledge. Economic growth must reflect changing flows and transformations of real materials resulting from micro as well as macro-technological changes. The electrification of the world, the rise and fall of the nuclear dream, the dependency of our civilization on power derived from the combustion of fossil fuels – a declining resource – are all examples of such changes. His more recent work has focused on this set of issues. One productive collaboration, with Katalina Martinás, has been to examine economic flows from an environmental stability viewpoint. It encouraged the authors to develop a novel approach to non-equilibrium micro-economics that is not limited to equilibrium conditions and is also consistent with the laws of thermodynamics. This led the authors to identify the atmosphere and the terrestrial biosphere quite early as the two most vulnerable systems in need of protection by environmental policy (Ayres and Martinás 1995, 2005).

Complementing Previous Nobel Awards and Advancing the Economic Sciences

The viewpoints presented by Ayres and his collaborators complement as well as modify certain insights provided by mainstream economics. Several of these mainstream views have already been recognized by the Nobel Committee, most notably those of Robert Solow, William Nordhaus, and Paul Romer. To put a perspective on the complementary data and insights provided by Ayres and his followers and colleagues, it is useful to quote Robert Solow: "*Ideally (such) modelling decisions should be made in the light of facts. Unfortunately, there are not a lot of usable facts to be digested*" (Solow 1994). Ayres's contribution is driven by a desire to enrich economic thinking by facts from the physical and material sciences, and by thermodynamics.

Robert Solow confirmed in private correspondence with Ayres (Ayres and Solow 2008), that he always saw energy as an intermediate commodity, a product of resource extraction and processing sectors, each themselves the result of accumulated capital and labor. He also reminds us, in his Nobel Memorial Lecture, how he was startled by the fact that "*gross output per hour of work in the US economy doubled between 1909 and 1949; and (that) some seven-eighths of that increase could be attributed to 'technical change in the broadest sense' and only the remaining eight could be attributed to conventional increase in capital intensity"* (Solow 1987). The Solow residual is that part of growth left unexplained in the Solow neoclassical model by sole increases in labour and capital intensities. It became interpreted, in a "deus ex machina" way, as the result of *Total Factor Productivity (TFP)* improvements in the economy. The absence of scientific grounding is the gap that Ayres and these colleagues in this new approach to growth aim to fill. As such this work might be listed as being part of endogenous growth theory.

In concert with Benjamin Warr, Research Associate at INSEAD, Reiner Kümmel, Physics Professor from the University of Würzburg, and Steve Keen, Honorary Professor at the University College London, Ayres developed theoretical and empirical studies showing that energy could largely explain the unexplained TFP part of previous studies. The relevant papers are (Ayres, Ayres, and Warr 2003) (Ayres and Warr 2005) (Kümmel, Ayres, Lindenberger 2010) (Keen, Ayres and Standish 2019). Using energy as a primary input, including for capital and labor formation, or as a third production factor besides capital and labor, these authors explain away the famous "Solow residual" as the contribution of exergy to production.

The approach followed by Ayres and his colleagues would have major implications for economics and national accounting, currently largely based on GDP. It would ask that GDP consider two fundamental quantities: the total energy harnessed to generate GDP, and the efficiency with which this energy is transformed into useful work (or exergy). Such an approach would lead us to address the "GDP paradox" identified by van den Bergh (2009) and stated by the latter as follows: "For over half a century now, the GDP (per capita) has been severely criticized as not adequately capturing human welfare and progress. All the same, the GDP has maintained a firm position as a dominant economic indicator, which can be regarded as a paradox … To resolve the paradox, or explain its persistence, one has to recognize the ambivalence with which many academic economists approach the criticism of the GDP indicator: they accept it but deny its relevance." The approach suggested by Ayres and his colleagues would lead us away from seeing GDP increases that are coupled with, for example, wasting fuel, increasing medical costs, or filling an empty lot with automobiles that just sit there without any contribution to fulfilling human needs. The type of accounting advocated by Ayres and followers would move economics closer to meeting basic human needs, as advocated by the Sustainability Principles promoted by the UN Global Compact.

There is a second point that differentiates Ayres's approach with Solow's neo-classical approach, which posits that the economy wants to approach a Walrasian equilibrium. Ayres views that technological innovations that drive economic growth are inherently exergy destroying disequilibrium phenomena, which are then followed by a search for a new equilibrium which persists until the new technology hits a barrier, like the last one did which it displaced. For Ayres, the economy thus never follows a sustainable equilibrium path (a fact consistent with the second law of thermodynamics).

The 2018 Nobel Laureates, William D. Nordhaus and Paul M. Romer, were rewarded for integrating climate change and technological innovations into long-run macro-economic analysis. They treated the material and physical aspects of the economy excessively as stylized abstractions. Nordhaus, as does Solow, assumes Total Factor Productivity increases (i.e. technological progress) continuously increasing into the future, presumably based on Romer's ideas of knowledge growth as a combinatorial process (a conclusion that Ayres qualifies, as we stated above). He also uses a standard technique of neoclassical growth economics, where the integral over an infinite horizon is kept finite by introducing "pure time preference" that discounts the future and makes the integrand eventually vanish. For Romer, the future is a bit different: for him, the global economy will continue to grow, in equilibrium, at historical rates, seeing the present climate transition – while temporarily costly – as a mere blip.

Perhaps even more debatable is Nordhaus's assumption that a large portion of the economy is preserved from climate change effects, seriously biasing his estimates on the cost of climate change. Because of the impact of Nordhaus's computations on the current climate change discussion, these assumptions deserve wider scientific debate and more grounded modelling, as argued by Keen and others (Keen 2020) (Keen, Ayres, and Standish 2021). The current controversies regarding Nordhaus's optimal time pattern of climate policy (notably carbon pricing) and its impact on the work of the IPCC, regarded as overly optimistic, precisely require contributions and breakthroughs of the kind Ayres and his followers have produced, founded on different and more accurate premises regarding the physical realities of the externalities produced by the economic system.

Conclusion

The work of Robert Ayres has had and continues to have clear implications for energy policy and decision making, and for society and the public at large. In all policy discussions, in all legislative and regulatory actions, and in all investments undertaken to ensure a more robust and sustainable future, legislators, business leaders, and the public at large should have a greater understanding of *industrial ecology* (or *industrial metabolism*) along with its methods of *materials accounting* and *life cycle methodologies* that are concerned with both the physical impact of economic activity on our planet. Ayres's contributions to these are fundamental and opened the way for this field to emerge as an applied economics area.

Secondly, the more recent work of Ayres, focused on considering the fundamental role of energy as an input into the overall economy, with its productive use of energy (referred to as *exergy)* and its wasteful complement (referred to as *anergy*) is most promising. It is a conclusion that emerged from Ayres's many years of investigation and effort. This dual look at exergy leads to a different and more precise examination of our energy options and exposes us more directly to the externality aspects of the energy transformation process. It also is emerging as another fundamental contribution, providing better foundations and linkages between economics and the physical sciences.

Finally, Ayres is like a voice that keeps reminding us that technological change can have catastrophic non-linear effects on society and cannot simply be discounted away or assumed to not hamper a harmoniously developing economy growing along an infinite equilibrium path. The Schumpeterian technological growth process is *not an automatic and smooth consequence of increasing knowledge and productivity,* as is still a prominent idea in current mainstream theory. *Technological change is discontinuous, destructive, and hard to predict because of multiple technological paths, and will be selected to respond to prevailing and perceived needs at a given time, without full and complete understanding of its longer-term consequences.*

A Nobel Prize awarded to Robert Ayres, possibly jointly to Herman Daly, would recognize critical and methodologically sound economic thinking outside the mainstream, aimed at achieving better and more accurate linkages with the physical realities of human life and activities on earth. Such an award could be seen as being in the same vein as the corrections that the Nobel Committee made when awarding the 2002 Prize to Daniel Kahneman (and implicitly his deceased co-author Amos Tversky) for introducing psychological biases in human decision making, modelled until then as the result of only rational thinking. The improvements in causal analysis made by the 2021 Nobel Laureates in Economic Sciences using natural experiments can be regarded similarly. Amid an environmental crisis of major proportions, a Nobel award to Robert Ayres would be a point that fully deserves being made.

We invite readers to turn to Robert Ayres's papers and books for further details on the major milestones of this remarkable scientific and human journey. We very much hope that the Nobel Committee in the Economic Sciences might lend a favourable ear to our nomination.

The Scientific Committee for the Nomination of Emeritus Professor Robert U. Ayres for the Nobel Prize in Economic Sciences:

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- Atalay Atasu, The Bianca and James Pitt Professor in Environmental Sustainability, INSEAD, Fontainebleau, France; Past President of the *Manufacturing and Service Operations Management Society* and Editor of the Sustainable Operations Department of the *Production and Operations Management* journal.
- Robert Axtell, Professor of Computational Science, George Mason University, Fairfax, USA.
- Robert Costanza, VC's Chair in Public Policy, Crawford School of Public Policy, The Australian National University, Canberra, Australia; former editor-in-chief of *Ecological Economics.*
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