Exhaustible resources – by Daniel Spiro

It is hard to imagine how the global economy, or even the world, would have been if mankind did not have access to and used of exhaustible resources. Minerals and metals have been used as tools, weapons and jewelry for thousands of years, and the start of the industrial revolution was mostly driven by the utilization of the steam engine where the energy came from coal. Not surprisingly, oil has been the most important resource the last hundred years, and its price and extraction is followed closely by both economists and politicians. Many countries put considerable effort into making sure their access to oil is sufficient, and this scramble for resource can even lead to revolutions and war.

So which factors control the extraction and prices of natural resources? Can the world economy persist without considerable extraction of, for instance, oil? Do the markets for natural resources work well? Is the global use of natural resources compatible with sustainable development and growth in the long run?

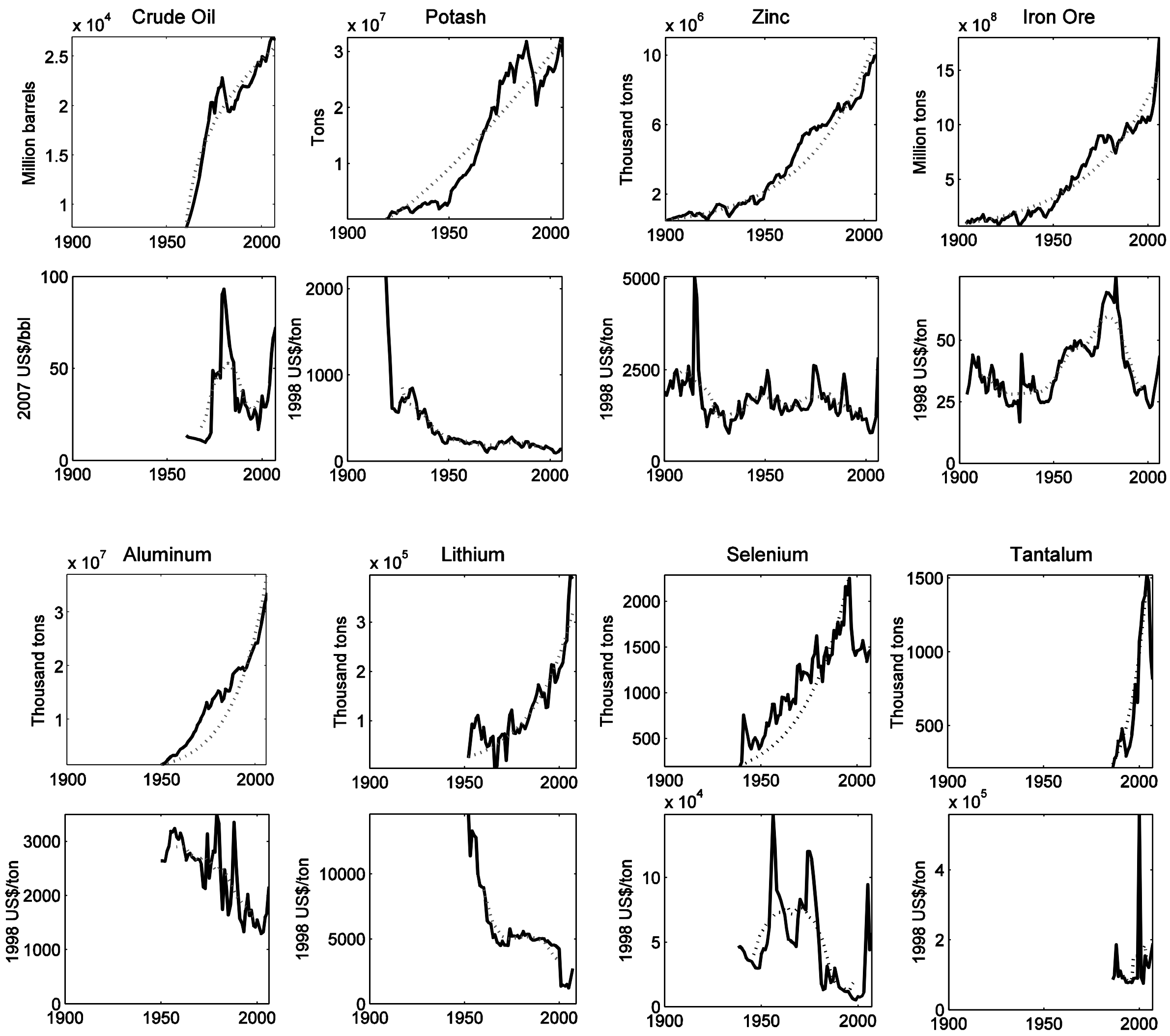
This article gives an overview of economic aspects affecting exhaustible resource markets. It will describe and give a general analysis of how these markets work, what imperfections there are, how such imperfections can be regulated and how one can distribute ownership of natural resources. One intention is to highlight if we, i.e. the global economy, optimally utilize these exhaustible resources. References to more detailed accounts can be found in the footnotes.

The defining characteristic of an exhaustible resource is naturally that they are exhaustible. As opposed to renewable resources, they are not rebuilt over time (at least not within a relevant time perspective). It is important to point out how this relates to our measure of production, for instance GDP, which is defined as production per time unit. Our access to *renewable* resources can potentially be unlimited over time if they are managed correctly. As an example, the amount of wood we can use would be infinite if we add together all chopped forest from today to infinity. In contrast our access to exhaustible resources is finite also over time. Hence, I will discuss economic limitations of exhaustible resources both per time unit (the effect on GDP) and over time (which affects, among other things, intergenerational "justice").

The figure below shows extraction and real prices (prices corrected for inflation) for a number of exhaustible resources during the latest century. It seems from this figure that:

1) Fluctuations in prices in the short run are considerable.
2) If one evens out the fluctuations, the prices haven't changed noticeably during the last century, on the contrary it seems a number of resources have had negative trends in prices[1].
3) The extraction has been steadily increasing, usually exponentially.

[1] We could also add that prices on most of the resources have increased over the last decade. However, whether this is a coincidence or a sign of more persistent changes in the price development is too early to say.



If one simply utilizes microeconomic analysis, one may conclude that a negative price trend follows from increasing extraction since the supply increases – a completely reasonable result for a well-working market. This is a common misunderstanding, founded in the assumption about exhaustible resources being a standard good. On the contrary, if one instead incorporates the exhaustibility of the resource in the analysis, it is quite difficult to explain increasing extraction and decreasing prices in a well-working market. The following section will explain why.

Market mechanisms

In order to decide whether the markets for exhaustible resources work optimally in practice, one needs to identify what controls the extraction and prices in the short run and in the long run. Theoretically, optimal extraction is achieved if the market works perfectly since all important aspects are then incorporated into the price[2]. I will in this section describe a series of mechanisms which should affect these markets at least in theory. The mechanisms will be described from how compatible they are with the empirical observations, how they affect

[2] As an example, the price should reflect the cost of extraction and transport, risk of a mine collapsing and the value of the resource to the buyer.

scarcity per time unit and how they affect scarcity over time. Indirectly, I will even argue that one cannot conclude that these markets work optimally or sustainably using present knowledge. The next section, which compiles certain market imperfections, will show that the contrary is more likely.

For a resource owner, the most important aspect in the long run, is the **total stock** of a natural resource and how it's used over time. The most common way of modeling the market for natural resources among economists, is to model how the market evaluates the scarcity. Let us, for a moment, disregard all other complexities and consider how a market of resource owners should behave if there existed no costs of extraction. The conclusion from such an analysis is that extraction should decrease over time, due to the agents discounting the future, which means they care more about their income and consumption today than they do about tomorrow. It is noteworthy that this simple model is contradicting all aspects of sustainable consumption, i.e. not decreasing consumption over time. Even if the extraction is optimal from the resource owners' point of view, it will decrease, and thus consumption decreases over time.

From such an analysis, it logically follows that the price should increase over time, exponentially with the interest rate level. This means that if the interest rate is five percent, the resource price should increase with five percent per year. This is because the resource owners consider the resource to be a real asset (at we theoretically assume they do). If they sell one unit today and deposit the profit in the bank, they will tomorrow have a return from this investment. If the price of the natural resource is expected to increase more than the interest, the resource owner naturally decides to sell this unit tomorrow. The opposite holds if the price is expected to increase less than the interest rate level. Hence, in equilibrium, prices increase at the rate of interest[3]. Furthermore, this model assumes each extracted unit gives a profit, a so called scarcity rent, which follows from the fact that the resource is exhaustible.

No matter how elegant and strong this result may seem, it is important to point out that it has very little empirical support. A quick glance at the long term price paths shows that prices on the contrary have been falling the last century. It is possible, though, to imagine there are other factors affecting extraction and prices than just scarcity, for instance **extraction costs**. Thus, the price will now consist of two components. The first component is the scarcity rent, increasing with the interest rate. The second is the extraction costs, possibly falling over time if we become more effective in the extraction. The total price may then fall if the extraction technology is improved quicker than the scarcity increases. Such a model predicts there will still be a connection between the interest rate and the price trend[4]. Holding everything else constant, a high interest rate should increase the price more (or reduce it less). Even this connection has very little empirical supprot[5]. Furthermore, is has been shown empirically that the extraction costs have been more or less constant over time[6]. Surely, the technological

[3] This might be the most well-known result in natural resource economics, it has been proven by Hotelling (1931) and Dasgupta & Heal (1974).
[4] Theoretically, this has been shown by Weinstein & Zeckhauser (1975)
[5] See for instance empirical studies by Heal & Barrow (1981), Abgeyebge (1989) and Halvorsen & Smith (1991)
[6] See Lin & Wagener (2007)

development has moved forward, but the potential cost reduction has been compensated by digging deeper and into less available areas, which leads to higher costs. We will get back to this.

The degree of **impatience** in the market is naturally important here. In the end, the market interest rate says how much the market demands in yield in order to postpone consumption from today till tomorrow. Hence, the market interest rate is a measure of (among other things) impatience. The more impatient the market is, the higher the market interest rate will be. The effect of impatience will increase the extraction today and thus reduce the price. But since this implies there's less of the resource available next year, the extraction must fall quicker and the price increase more than if the market was more patient.

Searching for **new supplies of resources** is important to the firms on the resource market and they invest a lot in prospecting. A popular explanation of falling prices is that we find new supplies, which leads to scarcity being reduced and hence reduction of prices. However, if one believes the market has rational expectations, this explanation cannot hold[7]. For a market to work well over time, agents must make correct predictions of what will happen in the future, at least on average[8]. If the market's agents have perfect foresight, they will predict new supplies being discovered. Hence, this will be incorporated into today's decision of extraction and thus into the price path before the actual discovery takes place. What happens then is that the price falls every time a new discovery is made, but increases in between discoveries. If the market for a long period, and repeatedly, becomes surprised by new discoveries being greater than expected, this long term price path may be flat. But with such consistent underestimation of new discoveries (for approximately fifty resources for many centuries) one can hardly say agents make correct predictions. If market agents have rational expectations (which means agents on average guess correctly about the future) they should as often be surprised the new supply was too small. Hence it is hard to imagine this can explain the long term price path if the market is perfect[9].

How we evaluate the potential of new discoveries also affects the view on how long we can keep utilizing a certain resource. Many say we should consider the resources as exhaustible from an economic point of view, not from a geological. By this, they mean that earth contains so large quantities of most resources that we won't be able exploit all of it no matter time perspective one has. But instead of geological scarcity firms need to **dig deeper and deeper** to reach the resources and the therefore the extraction cost decides how much we can extract[10]. The important conclusion from such a model is that the price should increase over time, followed by increased costs that may be compensated for by technological development. Even here, there should be a connection to the market interest rate, though of a more complicated nature, since the investors should decide whether "money in the bank" gives a higher yield than investing in digging deeper. There are only few tests of how the extraction cost is

[7] This is shown by Arrow & Chang (1982)
[8] Working well means here that the price is incorporating all important values and costs connected to the good.
[9] What complicates this explanation further is that it predicts the price path, between the new supplies, being connected to the interest rate, a prediction with little empirical evidence. See an earlier footnote for references.
[10] This is modeled theoretically by for instance Farzin (1992).

changed over time,[11] so it's difficult to say how much this model explains of the price- and extraction paths. Furthermore, it is hard to imagine this model setup to be applicable for oil where there are estimates of the remaining reserves which include the unconventional stocks of, for instance, tar sand. As for sustainability in consumption over time, a greater amount of extraction today may make it more difficult (or more costly) for future generations to extract resources.

Another mechanism that may affect the market is that we in the future will have other resources replacing today's oil, copper and iron. Hence, instead of digging deeper and deeper after the same resource, we find a close **substitute**. This is often called backstop-technology which means that (for instance) fusion power, if and when it becomes viable, will provide close to unlimited access to energy[12]. The most plausible effect this has on today's resources is that (compared to the case without the backstop) the extraction will be higher in the beginning and will decrease faster. This means the price will increase faster. Why? The owners of today's resources can be worried that, with a certain probability, next year there will be a new invention making their resources less valuable. In practice, this uncertainty affects the future so that expected profit from the resource is lower, in the same way as if the market was more impatient. And thus, they will extract more today, less tomorrow, even less the day after and so on. This leads to a price that is lower initially, but increases quickly. The qualitative predictions (that the extraction decreased over time, price increases over time and the price trend has a connection to the market interest rate) remain. For this to explain falling prices and increasing extraction, the market must with certainty know that a backstop-technology will arrive before a certain point in time. It's not enough to be certain it's coming at some point; we need to know that no later than a certain year, it will with certainty exist. If the market was able to set a maximum date, the price path could very well decrease if the resource supply is large. However, this does not seem reasonable for the resources in the latest century. For instance, even today no one can with certainty say when fusion or solar panel technology can replace oil at a large scale. Earlier in time the market was even less certain about this.

Also technological progress leading to **more efficient resource utilization** is sometimes put forward as an explanation for non-increasing resource prices. Theoretically, it can very well explain increasing extraction (in the short run) while the price path still should be driven by the market interest rate (and extraction costs). The argument that resource owners, in equilibrium, should be indifferent between extracting a resource or not still reamin[13]. Empirically, it is also quite difficult to see that more efficient resource utilization should have decreased the demand since the total use has steadily increased.

Finally, **recycling** is an important possibility regarding exhaustible resources. Recycling makes it possible to re-use a resource more than once. Mathematically, it is easily shown that if we can recycle half of all we use, it is synonymous with a doubling of the resource stock, and if we recycle 90 %, it is synonymous with a tenfold increase, and when we approach full

[11] One is Lin & Wagener (2007).
[12] See for instance Heal (1976) for a modeling of this.
[13] Theoretically, this is «easily» proven using Dasgupta & Heals (1974) model.

recycling, the resource supply goes to infinity. Some important notes, though, are in its place here. First of all, energy cannot be recycled. Hence, this is not a solution to the fossil fuel problem. Secondly, recycling also involves costs which naturally must be lower than the raw material price for this to be efficient. More specifically, recycling requires energy, which is both a cost and, ultimately, a scarce commodity. So there is a choice in the market between using energy for recycling or for other needs. In the end, the need for energy per recycled unit will go towards infinity when we are approaching full recycling. This may not be completely obvious, but it's governed by the law of nature called the laws of thermodynamic. In our context, this means full recycling of material is not possible even theoretically[14]. One could say that if we approach full recycling, the resource access per time unit is limited by our energy access per time unit. In that way, the exhaustible resource is transformed into a renewable one – potentially unlimited over time, but limited per time unit. It is hard to imagine increasing recycling explaining price- and extraction paths anyway. The amount of recycling is too small for it to affect the access to resources on a global scale.

The possibilities of developing a substitute, increasing efficiency in the resource use, finding of new supplies and recycling, are often argued to be a solution to the scarcity of certain resources. It is difficult, on a theoretical basis, to discard these possibilities. However, for this to solve potential scarcity of resources per time unit, there needs to be certain improvements to efficiency and the substitute needs to be developed quicker than the total consumption. This means the technical development related to resources must cover the population growth and the growth in production per capita. In order for the scarcity not to increase over time, the technological progress must compensate for the fact that less and less of the resources remain when we exploit them. An argument for natural resources not to limit the economy is that if we are low on resources, the prices will increase and the technological development catches speed since it becomes profitable to provide solutions to the problem. Some empirical studies also give support for this happening in practice. For instance, after the oil price shock in the 70s[15], energy efficiency seemed to have risen. For this to work completely, though, the market price must incorporate all important aspects and the future scarcity in particular.

Market imperfections

As mentioned earlier, long term sustainability is based on the assumption of well-working markets. This is since the price needs to reflect all important values and costs that consumption of the resource imply. As empirical studies show, and as described in the previous section, one can say that none of the market mechanisms we've looked at so far give sufficient explanatory power regarding the long term price- and extraction paths. This can be viewed as problematic, since it indicates the market are not working well. There are a number of market imperfections that should be discussed in this context.

In the oil industry in particular, it is clear that there is no perfect competition. The OPEC-countries control a great share of the world's oil reserves, and one could imagine they succeed

[14] For the connection between the laws of thermodynamics and economic activity, see for instance Smulders (1995) and Georgescu-Roegen (1971)
[15] See Hassler et al (2012)

in twisting the market to their advantage. Since the access of a number of resources is geographically concentrated, it is natural to believe the ownership will also be concentrated. Normally, the price is set higher when the sellers have **monopolistic power**. With exhaustible resources, where the resource will be spent sooner or later either way, it is not as clear how this turns out. Lower extraction today increases the price today, but leaves even larger reserves tomorrow, implying the price then will be lower. The monopolist must then choose between high prices today or tomorrow. Theoretically it is difficult to see how this should affect the price- and extraction paths qualitatively. It could well lead to either lower and more sustainable extraction or higher, and thus more sustainable, extraction today[16]. So even if monopolistic power actually does exist, it does not help us reconcile the empirical observations. It is even uncertain whether OPECs monopolistic power was what led to the unusually high oil prices in the 70s and 80s. On the contrary, research shows that price regulations, war and monetary policy are likely explanation for this[17].

Another mechanism connected to the concentration of owners is the observation that many **resources are state owned** rather than privately owned. It seems plausible that governments will consider political issues in their extraction decisions. It is hard to say how this should affect the price- and extraction paths. There is a vast body of research showing that wealth from resources may lead to corruption, worsening of political institutions, and reduced competitiveness in other industries etc[18]. But the economic research on political effects of natural resources has so far not connected this with market equilibria. One could imagine that state ownership leads to quicker extraction since the politicians, who potentially steal the profits, are worried about losing their position tomorrow. This might even lead to increased price fluctuations due to political business cycles. It could imply that extraction increases dramatically right before upcoming elections for the politicians to please the voters. If a country has a large share of the world's production, this might lead to increased price fluctuation. It is difficult however to see how political issues should affect the long term price path qualitatively. But if politicians have other aspects to consider, and do not concentrate on what is optimal in the long run, it would be a clear market imperfection[19].

Another type of potential market imperfections is the possibility that decision makers use **rules of thumb** when planning the extraction. For the resource price to be optimal crucially depends on market agents (no matter if they are political or private) having long term forecasts of prices and plans of extraction. To create such forecasts of prices, extraction, new discoveries, changes in ownership and technological development with a horizon of more than a hundred years ahead, is no simple task[20] . Were they to use rules of thumb, like doing short forecasts and plans of extraction, this would imply the total stock may be neglected as an

[16] See for instance Stiglitz (1976) and Gaudet & Lasserre (1988)
[17] Some contributions to this debate can be seen in Barsky & Kilian (2002), Hamilton (2003), Barsky & Kilian (2004) and Kilian (2009).
[18] See Rick van der Ploeg's (2011) overviewi article on natural resources' potential curse.
[19] In an experiment, van Veldhuizen and Sonnemans (2011) show that people ignore the long term aspect of resource extraction if the supply is large, and focus more on strategic aspects (like the ones from monopolies). If that experiment proves representative even for how politicians behave, it indicates that long term considerations (meaning considering future generations) are not implemented in the market.
[20] In economic research, this is often called «bounded rationality». See for instance Conlisk (1996) for a review.

aspect for the time being, since they do not limit the extraction in the present plan. This will lead to increasing extraction and falling resource prices over long time periods, and thus can explain the empirical observations[21]. Sooner or later, when the reserves are scarce enough as to limit the extraction even within the market's horizon, the prices will increase. This is a possible explanation of the increased oil prices around the millennium when the total oil reserves were estimated to run out within 40 years, which could be within the market's planning horizon[22]. Until then, the price will *not* internalize the scarcity, which can have multiple negative consequences. First of all, the extraction will be too high, which leaves a too low reserve for future generations. Secondly, and possibly more importantly, if the price does not internalize the scarcity of the resource the market will not receive signals in time to start searching for substitutes or technologies that would increase the efficiency of the resource use. Since it may be time consuming to implement technological solutions, there is a risk that scarcity will become a serious problem under a, possibly long, transitory period.

This sort of mechanism can be observed in a reasoning that has been popular in certain economic circles[23]. Since the prices aren't increasing, this is a sign there are no problems with scarcity. Hence, we can extract as much as possible. This will lead to no price increases, which then creates a self-fulfilling prophecy. The misunderstanding is that each market agent does not herself consider how much that is left of a resource, but believes everyone else does and hence that the price will internalize the scarcity. A very small limitation of the market agents' individual rationality, leads then to a potentially much larger market imperfection.

Quite a few exhaustible resources, for instance diamonds, have **undefined ownership rights**. This leads to extraction firms extracting as fast as possible, since what they leave can be taken by someone else. Every firm, and thus the entire market, will therefore ignore that a huge amount of extraction today leads to less extraction tomorrow and hence prices won't internalize scarcity. In practice, there are also examples of how this leads to war when different agents want to appropriate the resources. This is much like the situation when children (and perhaps even adults) are sharing a bag of chips a Friday night in front of the TV. Each person eats the chips as fast as she can, since what she doesn't eat right away will be eaten by others. In the end, this leads to the chips being eaten extremely fast and no one is incentivized to consider it might be more desirable if the bag lasted for the entire movie. Sometimes, fights may even break out in an attempt to hinder others from eating much.

Market regulations

How markets for natural resources should be regulated, depends on what mechanisms control the extraction and prices. One problem is that we cannot really explain why the price and extraction have developed the way they have over the last century – our policy instruments may then be badly constructed with severe consequences. In this section, I will describe regulations in two specific scenarios. One scenario is that the exhaustibility is the only aspect

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[21] See Spiro (2012)

[22] Another explanation, not contradicting this one, can be that the market consequently is surprised by the increased demand in developing countries such as China and India. If the market is consequently surprised, this means the market does not create correct forecasts, which is also a market imperfection.

[23] See for instance Simon (1996)

affecting extraction and that there are no extraction costs. The other scenario is that the exhaustibility does not affect extraction at all if the extraction costs and that instead other aspects are what control the market. A brief summary of how efficient different regulations are is found in the table in the end of this section. If reality consists of both these model worlds, the conclusions will end up somewhere in between what will be described in the following. The point of the clear distinction is to illustrate how different the conclusions might become[24].

In order to understand why, we have to go to the bottom of what differs between production of exhaustible resource and the production of any other good or service. Consider the hypothetical situation of visiting a pizzeria. The price is here, at least in theory, determined by the marginal cost of making and serving a pizza, and in equilibrium this marginal cost equals the marginal utility of the buyer. If we add a tax, such as value-added, on the restaurant this will lead to higher prices, since the marginal cost goes up and hence fewer visitors. If we instead, conceptually, consider an exhaustible resource where there are no extraction costs, the conclusion will be different. In this case, the entire price of the resource can be considered as profit for the owner – this is called scarcity rent. The price is then determined by the marginal productivity of the resource for the buyer. Suppose we put a value-added tax of 100% to the resource from now until eternity. This means that if the market price is two $, the owner receives one $ and the government one $. The owner still makes a profit on every unit sold, which means the entire resource reserve sooner or later will be extracted and we can immediately conclude the tax will not affect how much of the resource that will be extracted in total. Furthermore, since the tax is as large today as it is tomorrow and in ten years, the resource owner cannot earn more profits by changing the extraction path compared to the case without a tax. The conclusion is that the tax neither affects the extraction nor the price (which is equal to the marginal utility of the buyer). The only effect is that the government will receive (parts or all of) the profit[25].

If the point of taxation is to increase government income, this seems like a rather effective instrument since there are no distortions of the market. But if the point, for instance, is to reduce extraction due to negative impacts on the environment, a tax of this kind is pointless since it does not affect the firm's behavior over time or per time unit. In such a world, no constant tax rate can change the total extraction over time. To change the total extraction the government would need to implement a system of extraction rights with a limit for the total extraction.

If we instead want to push the extraction to the future (either to postpone climate change or because we believe more resources should be saved for future generations) we have to have a falling tax over time. To succeed, the tax must necessarily eventually become a subsidy[26]. This is since the tax must be reduced between every period, which means that the tax sooner

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[24] A partial description of this literature can be found in Hart & Spiro (2011)

[25] See for instance Dasgupta & Heal (1979)

[26] This comes from an assumption that, even many years from now, we will still want to postpone a proportional part of the extraction to future periods. If it is climate issues that push the extraction forward, the conclusion might be that the extraction eventually does not have to be further postponed and no subsidies are required.

or later will approach zero and that further reduction after this means a negative tax – a i.e. subsidy. This is easily shown analytically. The exception from this conclusion is if the tax is unlimited, so that the entire price ends up in the government, which is synonymous with nationalization [27] . Politically, this seems like two difficult paths to choose – either nationalizing or eventually subsidizing the resource markets. Even a tax that continuously changes is not easily executed politically.

Another conclusion is that expectations in the market may have unwanted implications. If we for instance say the tax on a certain resource will increase in a few years, this will lead to increased extraction today. Hence, the market should not be warned about future taxes, which contradicts the usual view that markets should get some warning so that they can plan ahead. The same goes for investing in research on renewable substitutes. These increase the risk of the exhaustible resource losing its value in the future, and hence extraction will increase today.

The problem with all the preceding conclusions is that they rely on the assumption that the resource's exhaustibility is the only factor controlling the extraction, or at least that it is a very important aspect. As discussed earlier, there are little (or weak) empirical evidence in support of this. Let us instead investigate how market regulations should work if there is an extraction cost, costs of searching for resources, for recycling and for developing substitutes. For simplicity, we assume that the resource exhaustibility does not play any role for how the market works.

If we then add 100% value-added tax to the price, once again so that the owner only receives half of what the buyer pays, we may very well have a situation where this does not cover the extraction costs. Or more precisely, the amount of extraction must be such that the price increases until the owner can cover her costs. Hence, just like in the pizza-example, a tax leads to a higher price and less extraction per time unit and over time. In the same way, a tax leads to less exploration of new reserves since the profits are lower, and lower profits from recycling (given that the recycled resource is taxed equally). If a future substitute is taxed lower, then research on such substitutes will increase. Likewise, a subsidizing of research will not lead to increased extraction today. The conclusion is that in this context, taxes can be efficient and we do not have to neither nationalize the resource, nor have a changing tax level over time (which eventually leads to subsidies) and nor go for limits to maximum extraction. The downside is that if the tax is used first of all as a source of income for the government, it will become harder to tax the firm without distorting the market.

Based on today's empirical studies, the latter scenario, that resource exhaustibility plays a small or no role, seems more relevant to use as a basis for analysis of which political instruments that work or not. But it can be difficult to say something general for all resources. For example, there are many indications that the oil market has started to incorporate the exhaustibility in their extraction decisions. A sign of this is that the oil price has risen the last decade. And in that case, the price should continue to increase even in the future and we end up in the first scenario. So even if the exhaustibility of the oil has played no role for the

[27] Alternatively, the tax can be implemented as «$ per extracted unit» (instead of $ per income unit). Such a tax can, even if it is not changed over time, affect extraction today. Nevertheless, it will not affect the total extraction.

historical oil price, it will play a large role in the future. Note however, that with taxation of the oil price, fewer new areas will be searched for while research of new substitutes will be more desirable.

The previous analysis mostly emphasized market regulations on a global level. A question one might ask is how a single country can affect the outcome in the market. Also here, it depends largely on whether the market is dependent on the resource's exhaustibility or if other aspects are more important[28]. Let us once again start out with the case where the only thing controlling the market is the exhaustibility. Then a one-sided unchangeable taxation over time in a single country will not affect the total extraction. Once again, since everything will be extracted sooner or later. This is not limited to a country being small or large. The price will increase in the single country, which leads to less resource consumption there, but at the same time the price will fall in the rest of the world until the resource owner faces the same net price in all countries. The extraction will remain almost unchanged per time unit[29]. In a climate perspective, this is called a carbon leakage which says that when the resource consumption in one country is reduced, it will increase in other countries. In a model world where the exhaustibility of the resource is important, the carbon leakage is large.

Another question discussed from time to time is whether voluntary reduced consumption in a country leads to preservation of exhaustible resources for the future. If the exhaustibility is the only aspect playing a role on the market, then this will not have any large effects on total extraction today unless the resource owners are convinced to prioritize future income rather than income today[30]. Another closely related aspect is whether emissions should be counted as the consumption or the production in the country. The problem is that if the production becomes greener in, say, Europe, emission-intensive industry will move to developing countries (still having no cap on emissions) while the Europe's *consumption* still leads to equally large emissions. In a world where the exhaustibility of the fossil fuel is an important aspect, this issue is highly relevant. Hence, it is necessary to have emissions quotas for all countries for locally cleaner production to be an efficient restriction of emissions.

If we instead consider a world where extraction and search costs exist, where a substitute can be searched for and recycling can occur, the conclusions will once again change to the opposite. A one-sided tax on natural resources will then reduce the demand in the country, increase the price and reduce the revenue of the resource owners. This will lead to less incentives to search for new reserves and thus it will affect the total amount of resources extracted in the long run. If one wants to reduce the amount of carbon in the atmosphere, this is a possible way forward. It will also give more incentives to develop renewable substitutes. Carbon leakage can theoretically happen in this scenario, but in a significantly smaller scale. In the end it depends on how the extraction costs are determined (whether they have increasing or decreasing returns to scale). For instance, if it is more expensive per unit to extract few units, then the world price might increase as an implication of one-sided taxes in a

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[28] It should be noted here that one-sided regulation still is an undiscovered field. What will be written here is based much on a simple analysis that might prove too simple in a more complex setting.

[29] Exactly how it changes depends on more specific assumptions.

[30] This can be implemented theoretically using a decreasing tax path.

country. This leads to a negative leakage, a sort of multiplier effect where the tax reduces both the demand in the country itself and abroad[31]. Even voluntarily decreased consumption of resources in a country will have a great impact in this scenario where other aspects than the exhaustibility play a role. This is because it does not lead to the same extent of carbon leakage. The effect of a one-sided decreased consumption can even lead to reduced consumption in other countries. In this scenario, the production constraint (instead of the consumption constraint) for emissions is a more efficient way of restricting emissions since high-emitting production to less extent moves to other countries.

The extent of leakage between countries is a highly empirical question. If we look at the history of natural resource prices, the latter scenario where the exhaustibility plays only a small role has more empirical support than the opposite scenario where the exhaustibility plays a large role. If the exhaustibility of the natural resources was an important aspect, the prices should increase, or at least there should be an empirical correlation between the price growth and the returns on capital. This has little empirical evidence[32]. If the exhaustibility is a less important component of the price of natural resources, this indicates the leakage is not large, or at least that it is not total. So far, there are few studies quantifying the leakage satisfactorily[33]. A few studies indicate the production does not move to other countries when a single country implements stricter environmental laws. This is possibly due to large costs of moving production between countries. If this applies also for production using great amounts of coal is thus hard to tell, since CO2-taxation in a large scale should lead to so large costs it might be worth moving the firm. To say something quantitative, on also needs to consider the effects on extraction and other costs on a global level from taxes and demand in single countries.

Finally, regarding market imperfections and the choice of consumption for generations today or in the future, it is not obvious which discounting factor should be used. So the question is whether the degree of impatience in the market, reflected in the market interest rate, is the discount factor the public finds correct normatively. Some suggest we should not discount the future generations more than the risk of mankind facing extinction. This deviates a lot from the discounting the market uses in practice[34]. How one should combine a high market discounting with significantly lower “moral” discounting is not an easy task even on a conceptual level.

The problem of exhaustible resources which are used too quickly is that the decision of extraction is irreversible. What we consumed yesterday cannot be consumed today[35]. All power is then given to today’s living generation. Even if the generations of tomorrow are

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[31] For such a market to work, imperfect competition is necessary, which is present in many resource markets. New areas where to look for resources are often controlled centrally, and this will lead to imperfect competition. In general, another important aspect of the resource markets is that there exist costs of entry, since one cannot produce minerals or oil if one has no access to an area where such exist.

[32] See an earlier section for an explanation of why and for references to empirical tests.

[33] For an overview of the literature, see Gars (2011)

[34] The market interest rate is on a level 3-10% depending on the investment, while the risk of mankind facing extinction is plausibly less than 1% per year.

[35] Alternatively, additional costs are required for future generations in order to recycle minerals we have already consumed and not recycled ourselves.

largely affected by our decisions of extraction, they have no say in the decision unless someone living today speaks on their behalf. This reasoning can also be applied to renewable energy and environmental issues.

Table: Summary of effects of market regulations

Intrument and reason	**Exhaustibility an important aspect**	**Exhaustibility not important aspect**
Value added tax (VAT) to decrease total extraction	Inefficient	Efficient
VAT to push the extraction	Inefficient	Efficient
VAT to get tax revenue	Efficient	Inefficient
VAT to reduce environmental effects	Inefficient	Efficient
Tax per sold unit	Efficient	Efficient
Emission cap for *consumption* in all or certain countries	Efficient	Efficient
Announce future taxes	Possibly efficient, but increased extraction today	Efficient
Subsidize research on renewable substitutes	Possibly efficient, but increased extraction today	Efficient
Reduced consumption in a single country due to considerations for environment or intergenerational equity.	Inefficient	Efficient
Emission cap for *production* in some countries.	Inefficient	Efficient
Emission cap for *production* in all countries.	Efficient	Efficient

Natural resource management

This section will briefly discuss different models of management of income from natural resources. In other words; how quickly should the natural resources be extracted and what should be done with the income. To analyze this question it is essential to first determine who is considered to be the owner of the resource. This means, which generations and which individuals should get the profits. This is a normative question which should not be answered (single-handedly) by economists. I will in the following assume 1) that the natural resource belongs to all generations equally, discounted to the market interest rate and 2) that it belongs to all individuals within a generation equally. Note that the first assumption is identical with a market perspective where the firms maximize their discounted incomes over time[36]. For simplicity, I also assume here that the country considered is small, so their extraction does not affect the market price. The income may be important for the single country but not large

[36] The alternative, that none or little discounting is applied, will be more complicated. Ongoing research analyzes such a scenario.

enough to affect the world market. For those who consider other property right scenarios more correct, parts of the analysis will change.

The expected development of the market price is crucial for how fast a resource should be extracted. If the price is expected to increase faster than the market interest rate, the resource should not be extracted[37]. If the price is expected to stay constant or decrease it should be extracted quickly. A country owning a natural resource has, roughly speaking, two alternatives for how to spread the income over future generations. One is to leave the resource in order for future generations to have income from selling it. The other is to invest the money in capital and let future generations use the capital and its returns[38]. In order to maximize the total income, extraction must occur such that the profits per unit, meaning the price minus the marginal cost of extraction, increases in the same pace as the interest rate level is. These incomes should later be invested so that interest will be achieved. The point is to spread the use of the natural resource income over generations and stabilize the income fluctuations of the government following the volatility of resource prices. A plan for withdrawal from the fund is then established from how much value one puts on the utility of different generations. A simple rule would be to simply consume the interest rate, but then future generations will have a larger income than today's generation since the fund increases when deposits are made. In order for all to get the same income, today's generation must spend some of the capital as well. Normally, the rules for withdrawal from the fund consider that the returns will vary with the business cycle. During "bad" years, parts of the capital will be spent on consumption (either government or private) and during "good" years parts of the profits are reinvested. This way, resource funds can be used to reduce cyclical patterns in a country's economy.

Another alternative is to reduce government debt with the resource money. This leads to redistribution over time, since future generations will have a lower interest to reapy. Yet another option is to invest for instance in infrastructure or research, making people richer tomorrow.

Finally I will briefly discuss the ownership of a resource within a generation. If one believes the resource belongs to every citizen of the country, there are two alternatives of ownership. One is that the resource is nationalized and the other is that it is owned privately, but that the incomes are taxed and later spread out over the population in an appropriate way. Purely theoretical, these are equals at first sight; since sufficient taxation in practice should mean the entire revenue accrues to the state and the citizens. One difference, though, is the dynamic effects of the taxes. If the government taxes the income of the natural resource heavily, but otherwise is not engaged in any resource activity, firms will not be willing to search for new deposits or improve the extraction technology. This is because it does not lead to (large enough) revenues for the firm itself when taxes are high. Thus, there is a balancing of taxation between getting a large part of the cake and increasing the size of the cake. This balancing is certainly found in every economic activity, but what makes it even more problematic with exhaustible resources is if one believes the incomes in fact belongs to everyone, in and

[37] Strictly speaking, the price minus operating costs is what should increase faster than the interest rate.
[38] This can follow the so-called Hartwick-rule (1977) saying that if all natural resource income is invested in capital, a country or an individual can maintain the consumption level even when extraction ceases.

between generations, and that extraction decisions today are irreversible. If the government owns the resource and is engaged in the search for deposits, this balancing disappears since the same agents creates the revenue and searches for more deposits. Certain disadvantages with governmental activity can probably be discussed as well; most importantly it seems that large external costs lead to corruption. But whether this is an applicable problem in a specific case and whether it outweighs the taxation problem implied by private ownership, is beyond the scope of this brief review.

Is economic growth possible and desirable?

We have now reviewed the most important aspects of what should affect the markets for exhaustible resources and the distribution of the income. This may then be a good point to review an ongoing discussion between advocates and critics of economic growth regarding technical change and exhaustible resources. Let us for simplicity disregard any misallocation of incomes in the world. This naturally affects who should benefit from the growth, but does not affect as clearly if growth is *possible* on a global scale. Advocates of growth often point out that technological development will solve possible scarcity, especially since the price will create an incentive to conduct research. This implies that they 1) consider resource markets to be working well or at least that they are within reasonable range of correction of possible imperfections and 2) believe technological development is possible in the long run.

Based on the review in this chapter, it is hard to conclude that resource markets work well. Partly, the market based models cannot explain the price and extraction paths and partly there are too many obvious market imperfections – such as political interests regarding resources and information problems on for instance how large deposits will be discovered in the future. Regarding the possibility of technological development, critics of growth point out that there are limits for how much more efficient resource utilization can become[39]. Among ecological-economists the laws of thermodynamics are often used to support this claim. The second thermodynamic law implies among other things that the amount of resources per production unit have a lower boundary which is larger than zero. This eventually will set a limit to increased energy efficiency. One could ask why we should bother about this boundary – one could let the growth continue as long as the limit is not reached, and then let the economy level out when we approach it. This reasoning, however, becomes a little problematic with exhaustible resources since today's consumption prevents future consumption. If we are close to the limit for resource efficiency, it becomes harder to keep the consumption level for future generations at the same level if we consume the resources today. If, on the other hand, the limit imposed by the thermodynamic laws will be relevant only in the very far future, a large scale resource utilization today will affect future consumption negatively only in the very long run, not the near future. To the best of my knowledge, no one todays knows how close we are to this boundary. Furthermore, the future technological development is not something we can say by certainty will happen. Market mechanisms can certainly lead to greater *investment* in technology. Historically, these investments seem to have led to technological breakthroughs and solutions. Whether this is going to lead to technological *solutions in the future* dealing

[39] See for instance Smulders (1995) and Georgescu-Roegen (1971)

with problems that will occur in the long run, however, is based more on belief since there are no certain answers to such questions. What to believe about this uncertainty and how it should be handled from a perspective of fairness is not something economic research has an answer to.

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