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State-of-the-art research:
Reflections on a Concerted Nordic-Baltic Nuclear Energy Effort

by

Lars Husdal, Jesper Tveit, Jan S. Vaagen and Danas Ridikas

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Abstract

Quite a few hold the view that nuclear energy will have its renaissance in the not too distant future. Technology is, however, a necessary, but not sufficient condition. The needed prerequisites represent a complex issue. With increasing energy demand and depletion of non-renewable energy resources, nuclear will have to prove its role in an increasing energy mix, globally, regionally and often also nationally. Based on its history, experience with coordinated interplay in electricity production from a variety of energy sources, and science engagements, we argue for a future Nordic/Baltic SHOW CASE: A nuclear weapons free and proliferation safe nuclear energy supplier in the region, with a concerted role in competence building and in international ventures, and with focus on operation, safety, economy and societal aspects.

Contents

1 Prelude

The World needs visions for how to get 'beyond petroleum' (including natural gas), but also a roadmap, realistic time perspectives and young people who share the visions and are willing to devote their lives to the cause. To bring knowledge-based insights forward and to stimulate collaborative measures is a prime goal. It may be useful already at the outset to recall the definition of the word *sustainable* given 20 years ago (1987) in the report "Our common future" by the World Commission on Environment and Development under the Chairmanship of the former Norwegian Prime Minister Gro Harlem Brundtland. The commission, set up by the United Nations, made the now accepted definition of *sustainable development* as development that "meets the needs of the present generation without compromising the ability of future generations to meet their own needs". This definition implies substantial foresight, foresight which can only be achieved by cross-disciplinary efforts, that is talking with each other not only to each other. About energy, "laissez faire" is not good enough. The Economist reported recently that in the two years 2006 and 2007 China created a total extra generating capacity larger than that currently available in the whole of France; by building new coal-fired power stations! This prelude will focus on three main points.

A. We live in the nuclear age. We will continue to do so, quite independent of if we like it or not.

B. Nuclear technology already underpins vital aspects of our global society, in peace and for war. Worries linked to long term climate change issues must not jeopardize our nuclear awareness, control and competence. Nuclear neglect will certainly make future development less sustainable with possible catastrophic consequences.

C. Nuclear energy may help create a bridge 'beyond petroleum', through a century of decreasing available/affordable petroleum and gas, thus buying us time to develop the energies of the future: Large scale clean coal, solar energy, breeder reactors with waste burners, and fusion imitating the Sun.

A. WE STILL LIVE IN THE NUCLEAR AGE AND WILL CONTINUE TO DO SO
Are we aware of it, and how? Ten year ago the physicist Freeman Dyson [1] wrote that "The disappearance of nuclear weapons from our thinking about the future is a historic change for which we must be profoundly grateful. Fifty years ago and for many years thereafter, nuclear weapons dominated the landscape of our fears." But Dyson adds that "Now, quietly and unexpectedly, the bombs have faded from our view. But they have not ceased to exist. The danger to humanity of huge stockpiles in the hands of unreliable people is as real as ever. Yet the bombs are not mentioned in our vision of the future. How could that have happened?". Dyson found the answer in a technological and political development that gave no military advantage to the owners of nuclear weapons in real-world conflicts. Ten years later we may add that the case of Iraq has testified to this. Still, however, remnants

from the Star-Wars missile defense scenario of the 80s' have recently popped up again, certainly involving nuclear warheads, although not mentioned explicitly. A sustainable future requires that we truly reverse the arms race by getting rid of the useless surplus of war heads, and that we find useful ways to burn the stockpiles of plutonium and depleted uranium, from both civilian and military activity. A future, where the nuclei of matter serve mankind for peaceful purposes only, is not an illusion and may eventually come through. But young people have to make the vision their own, and be given a chance to make it real. It will take time and money, but also be intellectually fascinating. Petroleum will still be essential for our near future, but being forced to see 'beyond petroleum', money surplus from just petroleum should be spent to develop the next to near future.

Some quarters have tried to play down the role of nuclear power in electricity production. This is neither fair nor correct. It is in fact dangerous demagogy. Presently, 1/3 of EU's electricity is produced (around 125GWe) by 144 reactors, a third of the total number (436[1]) in operation world-wide. Energy supply and energy security, also safety issues, have become top EU priorities. EU is a major partner in forwarding development of Generation IV nuclear reactors, with a 30 years commercialization perspective. To meet the energy challenge, scientific organizations have been called on and relationships to policy-makers have been strengthened, via bodies such as EASAC (European Academies' Science Advisory Council) and the European Physical Society (EPS), which recently published its Position Paper "ENERGY FOR THE FUTURE - The Nuclear Option" [2]. Thorium's present revival in Norway, sparked off at the Energy Foresight Symposium 2006 in Bergen, with follow-up meetings in academies and other bodies, had particular focus on sub-critical Accelerator-Driven Systems (ADS). Subsequently a wider range of more conventional reactor concepts has been addressed. Support from the academies KVA/IVA in Sweden, from Finland and from European networks already mentioned, has created wider international attention. The public in Norway and the media have in particular been interested in two questions; (i) Does nuclear power need thorium, and (ii) Does Norway need home-based nuclear power? The ongoing public debate has addressed both a country's responsibility to explore its natural resources, and not least Norway's moral obligation to have nuclear competence in the nuclear age, and in a wide sense.

B. UPHOLDING NUCLEAR COMPETENCE

A century of cheap oil and gas could have fuelled a more rapid development of nuclear technology and competence - It did not [3]. Investments in energy research have generally declined in the last decades instead of gone up. To make it into the future in a sustainable way requires drastically changed investments in energy research. The energy sector creates, according to the International Energy Agency (IEA), 10% of the global GDP. Japan, the best boy in the class, invests less than 0.1% of its GDP on energy R&D. Despite US and EU moratoria on new nuclear reactors, the nuclear industry has been quietly working to solve its 20th century technical problems. It has learned a great deal about safe, efficient operations, and about design of third generation systems which are far cheaper to build,

[1] March 2009

disassemble, and decommission. The moratoria have, however, affected the human capital base, calling for urgent reinvestments and recruitment drives, both in universities, institutes and companies. In a few years time, a substantial part of the relevant nuclear science community will be gone, on pension. Those who want to get rid of all nuclear right away, should keep in mind that also decommissioning requires expertise and takes time! Historic lessons have made the scientific community point out that the basic nuclear science should not be sacrificed to finance ventures in energy innovation. Basic and applied need each other more than ever - and the communities are getting together again.

C. NUCLEAR POWER - BRIDGE "BEYOND PETROLEUM"

Supply security has recently made energy a regional collaborative concern such as within the EU and expressed in EU's Green Paper from 2006. This, probably more than environmental concerns, has triggered the political awareness. The endless ongoing debate in the media, a debate which has become apocalyptic addressing the "to be or not to be" for mankind, should not take focus away from the central reality that we need energy to uphold our civilization. Addressing the interplay between energy and survival of our environment the way we like it requires build up of knowledge over considerable time, in a society of changing possibilities and measures.

Thus, energy must increasingly become a knowledge driven common concern in our fast growing global society, knowledge in a wide sense. Science and technology have provided a fundament for a civilization based on energy, electricity in particular, and petroleum in the transport sector. We have an obligation to look forwards beyond our own lifetimes; The amount of easily accessible energy is limited and we need to map out potential sources properly. The European Physical Society (EPS) in its recent report [2] addressed use of thorium, also in association with accelerator driven systems (ADS), to fall within a time horizon of a generation, if we go for it, and with possible partial applications before that time, in particular for destruction of nuclear waste. An ADS, also called a nuclear amplifier, is an alternative to a conventional nuclear reactor by among other tings operating sub-critical, minimizing the risk for running out of control (meltdown). The idea was first put forward in the 50's by the Nobel laureate E.O. Lawrence, of Norwegian heritage, and revived in 1993 by another Nobel laureate, Carlo Rubbia (CERN) based on the substantial accelerator developments in the years in between. Thorium, also thorium + ADS, opens new perspectives on global energy supplies, with less but not without challenges linked to waste and non-proliferation. Norway has a significant part of the World's thorium resources. Norway also played a visible role in the first phase of the atomic age, promoting 'Atoms for Peace' internationally via spokesmen such as Gunnar Randers, and building the first reactor (research) outside the monopoly of the big powers after the Second World War. Discovering oil and gas in the early 70's changed the priorities. Instead of going nuclear, Norway became one of the World's biggest petroleum exporters. Now, at the culmination point of the oil age, and with environmental concerns related just to fossil fuels, nuclear energy is of renewed interest - thorium in particular. Thus the Norwegian government asked for a broad based evaluation of the thorium issue. And the report of an international committee was released in February 2008.

A global annual energy consumption increase of 3% represents a doubling rate of 24 years, and would lead to a multiplicative factor of 16 times the present energy consumption by the end of the century. Nobody believes this will actually happen; a factor of 4-6 is more likely. These estimates do not include the substantial energy that would be required by CO_2 sequestration and production of hydrogen, clean water and food. One may not share the current concern about CO_2, or be conservative concerning realistic time horizons, still most people now agree that a knowledge based energy future is strongly called for. And we have to start now, years of neglect also in the educational sector has led to reduced competence and lack of young blood. All realistic options have to be explored, while we still have resources to invest, and nuclear energy has again become part of the public debate. It does not produce CO_2, and it is a concentrated and efficient way to produce large amounts of electricity and heat, and in the future also hydrogen. It does however still have to deal with its own wastes, safety issues and non-proliferation questions. Fission energy also needs fuel. There is three times more thorium than uranium on Earth, and we may proceed from a uranium age to one where thorium increasingly comes to play. In addition to the ONLY available thorium resources India, for example, up to recently have been working on the nuclear energy scenarios based on the thorium fuel cycle and operate test reactor with 233U as a fuel.

Although the US, the UK, and many other countries have largely dropped out of nuclear power research, the French, Japanese, and Russians have maintained vigorous programs. In a hot energy market one must, however, be realistic about the number of new reactors the world could physically build in the two decades ahead, even if the money and determination were present. The ongoing Finnish Olkiluoto reactor project provides good calibration. Still one must be optimistic and hope that nuclear power can do more than keep its relative position in the global power production. If decisions are made now, we may also hope to have tested waste burners, such as accelerator driven systems (ADS), within two decade's time. Alex Bradshaw [4] has put up an "energy agenda" for the future. It contains four points;

1. To promote the use of renewable energy forms (provided they fulfill sustainability criteria).
2. To achieve a more rational use of energy.
3. To improve the efficiency of energy conversion processes, and
4. To explore fully all future options even if some of them do not necessarily fulfill the strict definition of sustainability.

The Thorium Report Committee's [5] first recommendation emphasizes the last point, "No technology should be idolized or demonized".

2 The Hansa Legacy

The authors of this paper come from former HANSA cities, the subsidiary kontore KAUNAS, and the principal kontore BERGEN (Bryggen). "In its early days the Hansa League aimed to consolidate the legal rights of anchorage, storage, residence, and local immunity, which its members required to conduct their business. It was also concerned to stabilize currency and to facilitate the means of payment. (The English word sterling derives from 'Easterling', an epithet widely applied to Hansa merchants". All this, according to Norman Davies' book "EUROPE - A History" [6] from 1996.

And Davies goes on; "The legacy of the Hansa long outlived its demise. Over the centuries it had created a way of life whose solid virtues were cemented into every stone of its bustling and elegant cities. To be Hanseatic was to belong to an inimitable, international civilization based on shared values and priorities". "In European history the (Hanseatic tradition) shines like a beacon for all who seek a future based on sturdy local autonomy, international co-operation and mutual prosperity". It may be argued that the Hansa was a precursor to present days Nordic/Baltic networking, and to EU itself. Lessons from the Hansa's 500 year operation appear also to be relevant today, in particular for the field of ENERGY.

'Carta marina' of the Nordic-Baltic Sea region from 1539 (Fig.1) shows the region at a time when the Hansa had just peaked, with growing challenges, in particular from the East.

3 Hansa Competence: Interplay and Outreach

Not only did the Hansa 'fuel' Europe with materials such as metals and timber from the North and East, it also provided training within its guilds, and commanded intellectual capital that enabled it to dominate the ship building market for centuries, selling ships everywhere in Europe, as far away as Italy. The Hansa provided tools for mobility and communication, linked to shipbuilding and seamanship, to master the ENERGY of that time, WIND and WAVES. Our shared regional history, and also the intrusions and interactions with mighty neighbors on our borders, have provided us with useful lessons underpinning reflections on a concerted Nordic-Baltic energy future.

4 Present Nordic-Baltic Energy Consumption Profile

Fig.2 shows the current total energy consumption profile for the Nordic-Baltic region. We notice the great variety, displaying a region of exceptionally wide energy competence. In the energy mix F(fossil) + R(renewable) + A(alternate) = T(total), the nuclear component (in A) is considerable in Finland and Lithuania, and particularly so in Sweden. Its relative role in electricity (power) production is even larger. In appendix D.4 we discuss a proper derivation of transitions from F to R and A. Fig.3 is a modern map of the region, where the number of power- and research reactors in each country is indicated. The Nordic-Baltic

Fig. 1: Carta marina

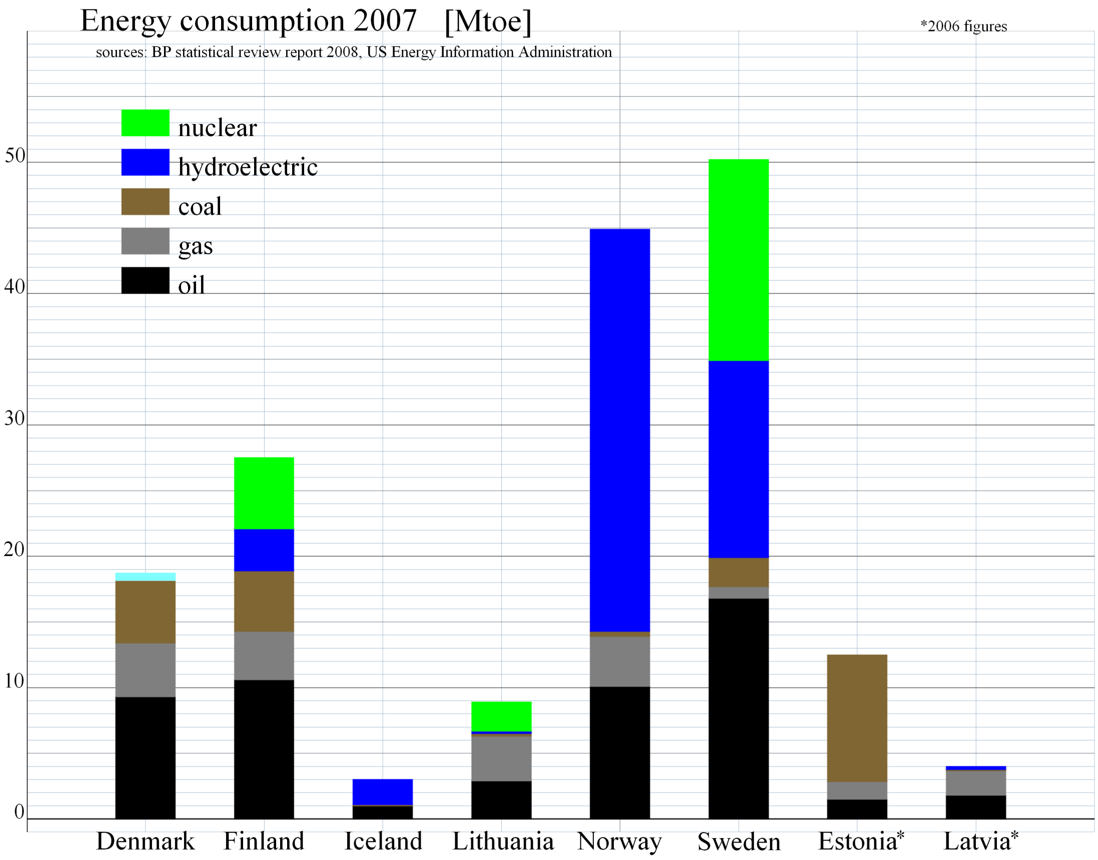

Fig. 2: Nordic/Baltic Energy Consumption

nuclear community is still large, and with a proud history in nuclear science and energy research. The Nordic countries were among the first to build nuclear research reactors after World War II, outside the monopoly of the Great Powers. We will return to this in focal point A. Finland is a pioneering country in our times and in the process of constructing the first European EPR 3+ reactor, developed by French Areva and German Siemens.

5 Energy Resources: Trade and Export

The Hansa developed a regional structure and provided a larger market with 'fuels' and transport solutions. Norway has for a few decades been one of the world's largest exporters of oil and gas, and is a major European supplier. The activities are now moving north. Fig.4 and Fig.5 show a recent scenario for the petroleum development. What may happen on the Russian supply side within Russian territory will certainly also pass close to Nordic-Baltic territories. We will return to the challenges in the North in a nuclear context.

The NORD POOL, a Hansa-like grid structure, is a Nordic tool, primarily for integration within the Nordic electricity market, and in many ways a show case for such operations. It also provides links to the continent where Nordic companies such as Vattenfall are vis-

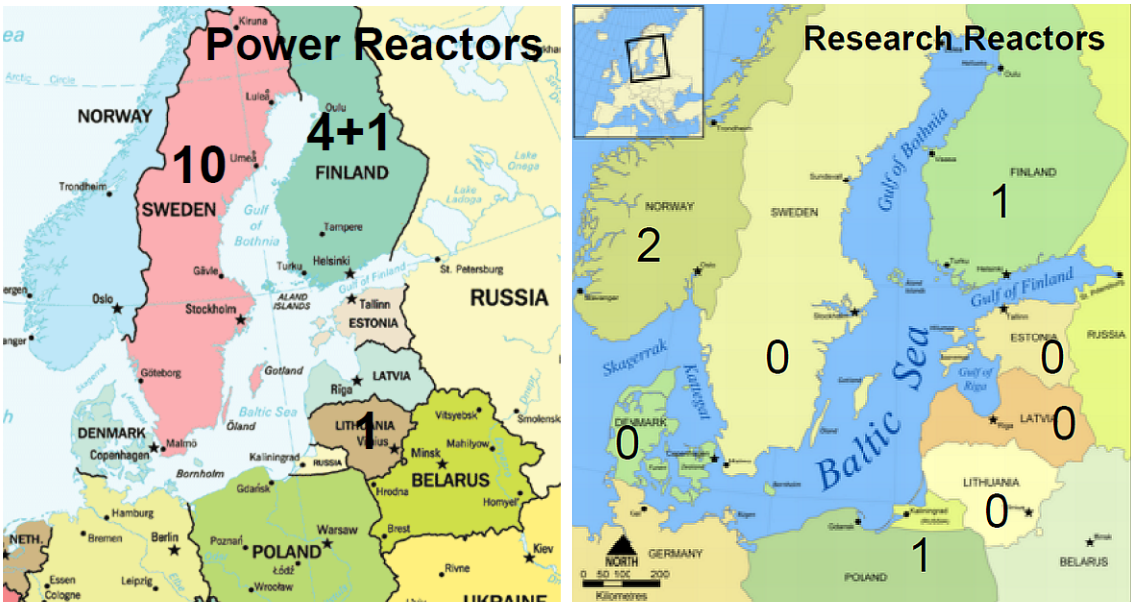

Fig. 3: Nuclear power reactors and research reactors in the Nordic/Baltic region

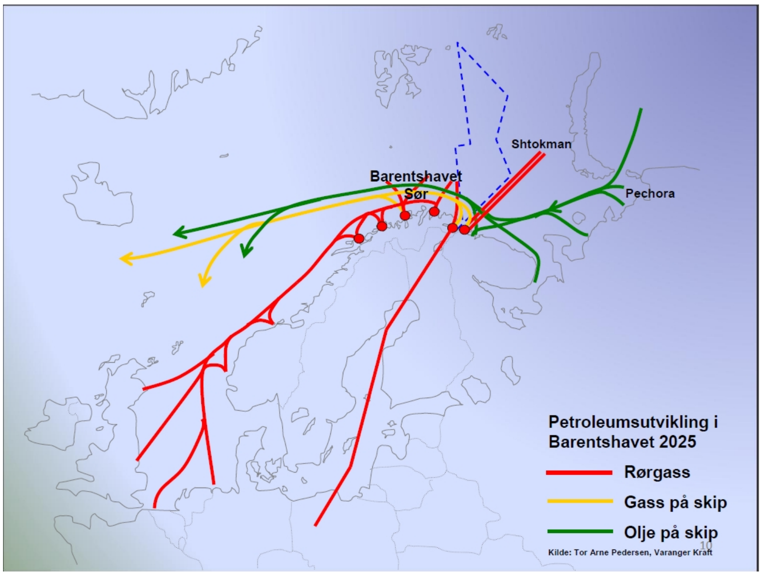

Fig. 4: Petroleum development in the Barents sea

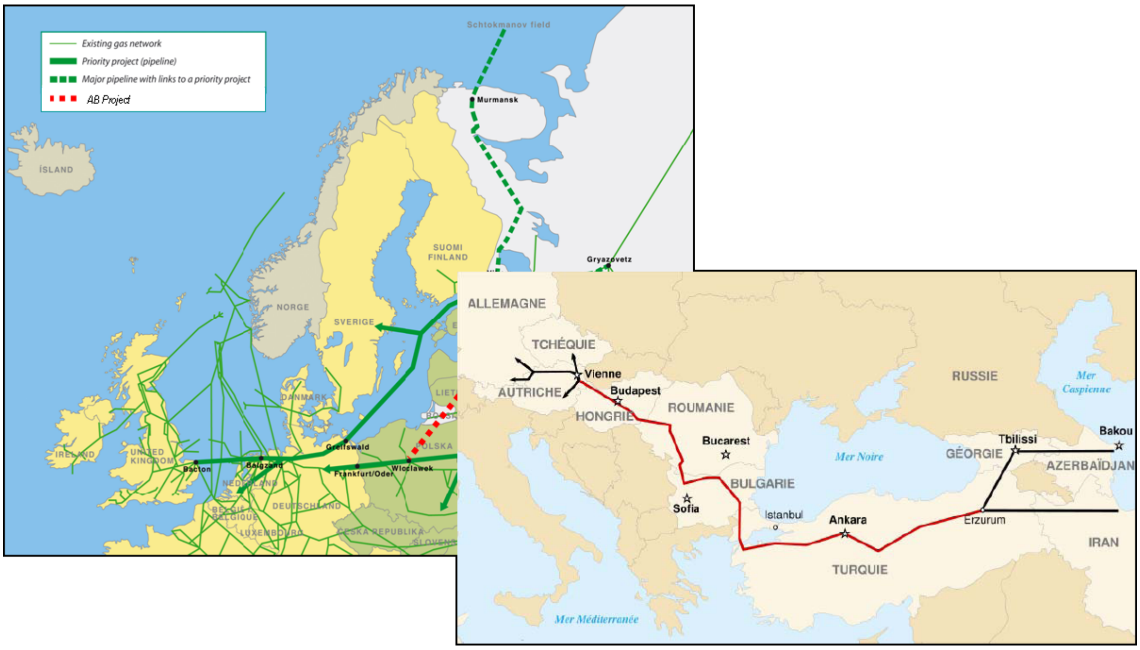

Fig. 5: Upper left: Russian gas supply to Europe (directly without any transit country) Lower right: Gas provision to Europe independently on Russia

ible players. The electricity systems bequeathed to the Baltic by the 50 years under the Soviet 'umbrella' (which ended in 1991), have hindered attempts at comprehensive energy integration. Currently a cable from Estonia to Finland called Estlink is the only major connection joining the Baltic to the Nordic grid. A further link, Estlink2, is in an advanced planning stage. Measures to terminate the status of the Baltic States as an isolated island have been discussed both in the Nordic Council and Baltic Assembly. Fig.6 gives a Baltic perspective. Nordic Energy Research, a tool for the Nordic Council, has just been evaluated and found to be a visible player of great value for transnational networking and also for decision makers. Energy Forum EF in Bergen has obtained valuable start-up support, allowing it to become a recognized player in joint ventures with Nordic (and Baltic) academies and European bodies with energy high on their agenda.

Fig.7 deals with the uranium fuel situation in the World, showing produced uranium, demand and projections. In a few decades time the fuel situation will become critical unless the way we run reactors includes breeding, or new fuel cycles, such as that of thorium, are included. Focus on Norwegian thorium resources sparked off a renewed nuclear energy debate in Norway a couple of years ago. This has helped secure further operation of the Kjeller/Halden research reactors, and also strengthened the understanding that Norway cannot leave the Atomic age (in spite of its oil and gas), having to take its share in maintaining nuclear competence and safety. The Estonian experience with extraction of rare earth elements, minerals, (including hafnium and lanthanum) may here be useful. This activity is carried out at an ex-Soviet uranium extraction and fuel fabrication plant. The extraction of rare earth minerals requires large amounts of ore for their production,

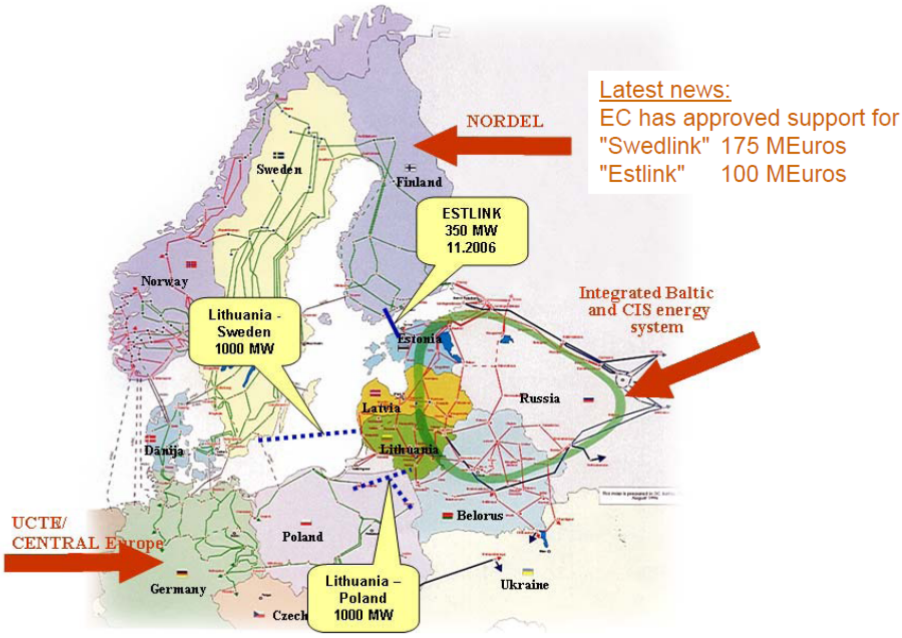

Fig. 6: Strategic electricity interconnections in the Baltic region

not so different from problems related to the finely grained Norwegian thorium deposits.

A new business area, that of CCS (carbon capture and storage), is about to start up. It is driven by public (political) climate-change worries, emerging from scenarios for the future created in the scientific community. It may seem a paradox that just petroleum/ fossil fuel companies, that have produced and still produce the CO_2 surplus, are now spokesmen for CCS waste handling, (apparently hoping however that society will carry the major initial costs). Shell as an example, has in its Blueprint scenario proclaimed coal and CCS the most likely winner by 2050. Norway (StatoilHydro) and Sweden (Vattenfall) have already very visible roles in the upcoming business area of CCS.

6 Carbon Waste Deposition. Similarities with Nuclear Waste Handling - Possible Joint Ventures?

Very recently (January 2009), the Norwegian government decided to initiate the construction of the Norwegian CO_2 handling test facility at Mongstad north of Bergen, injecting 5GNOK into the project. This as part of the so-called Norwegian moon-landing, announced by the Norwegian prime-minister Stoltenberg, New Year's day 2008. The ambition is to put 100 000 tonnes CO_2 per year beneath the sea floor from 2014. To start with, the CO_2 will only be captured and 'let loose again'. Capture will initially be an up-scaling of traditional amine technology.

Permanent nuclear waste handling has been put aside, mainly due to public debate, and is still a debated issue; All Nordic reactors and also Ignalina still store their waste over

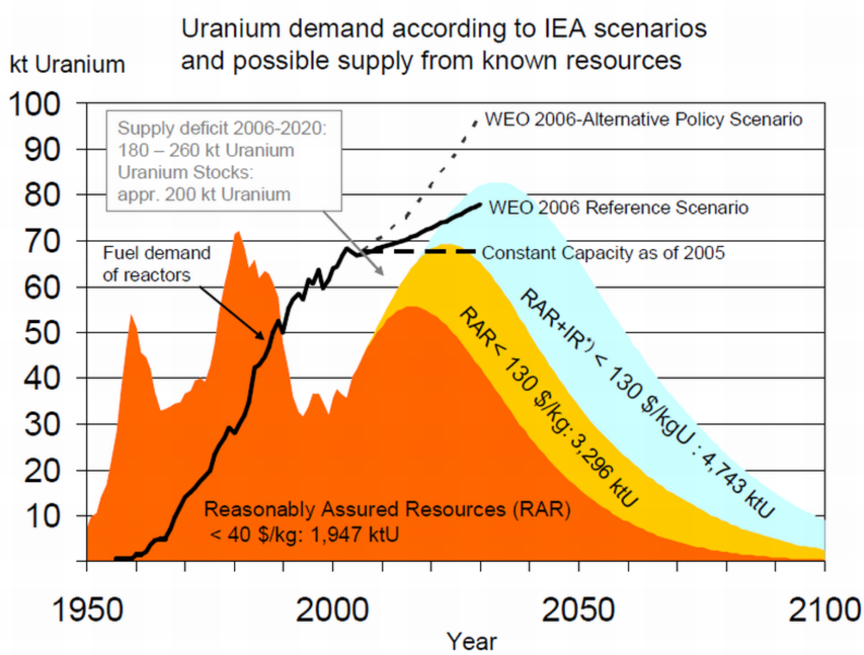

Fig. 7: Uranium production, demand and projections [7]

ground at the sites. Now a similar debate is emerging concerning CO_2. One aspect is the cost, CCS will imply 20-40% increase in fuel consumption and reduced efficiency for gas and coal fired plants.

Norway, based on its North Sea experience, considers CCS to be a future business area, and aims at offering Europe both infrastructure for transport and storage. This is however no free ride! In the leading Norwegian West-Coast paper, Bergens Tidende, professor Peter M. Haugan [8], a leading geophysicist at the University of Bergen, addresses the issue 29 January, with a warning! (Our translation). "A main problem in the Norwegian debate on CO_2-handling is that (underground) storage has been presented as unproblematic, cheap, and available today. Thus one has succeeded to appear in a green shine in forwarding this as a transition solution to a future of renewable energy, beyond petroleum. To present things this way is highly deceiving. There is today no experience that underpins consequence analyses for storage projects of CO_2 from power plants. Regulations for evaluation and acceptance are still not in place, neither in Norway, in the EU nor under international conventions. Nobody can guarantee any project to be permitted. Nobody can today tell which documentation will be required or which investigations that will have to be done or what the cost will be, neither for the geological North-Sea Johansen-reservoir formation, relevant for CO_2 from Mongstad."

Thus the situation is not that different from that of nuclear waste handling, and joint venture possibilities should be looked for and investigated. The costs are large in both cases, and there is a common need for research and training of competent personnel. In spite of the current economic set-back, it appears that CCS will continue. Nuclear

Power enthusiasts, some using the CO_2-free argument, some disbelievers in a man-made CO_2 threat, should both have a second look at how possible joint ventures may advance fundamental understanding relevant for both issues. We will return to this in focal point B.

7 Nuclear Serving Fossil Production under Extreme Conditions

Petroleum production from 'dirty' sources (oil/tar sand) or under harsh weather conditions, such as in the Barents Sea and in the Arctic, calls for cheaper energy (electricity) supply to harvest the increasingly valuable petroleum products. Nuclear energy is now becoming an affordable option. For the Shtokman gas field, nuclear electricity is being considered produced by barges or submarines that may be moved away when weather gets bad or ice(bergs) threaten. The nuclear aspect of such future operations is certainly a concern, being addressed also by the Norwegian partners, StatoilHydro being one of them.

8 Co-operation With Russia

In 1478 Ivan III (the terrible) closed down the entrepreneurial independence of the principal kontore of Novgorod. National control of natural resources and human capital has been a recurring theme since the formation of national states. Energy is in particular such an area. Since however its technology is underpinned by international advances, some collaboration is desirable, also for Russia, as evidenced by the plans for joint ventures with France and Norway on gas exploration and production in the Barents Sea.

In nuclear science Russia and the Nordic-Baltic countries have collaborated in knowledge building since the field emerged in the first part of last century. Both parties are now-a-days faced with the challenge of renewing their competence base, also for nuclear energy production. Aging Russian reactors across the border is also a growing problem which best can be approached in openness and collaboration.

Russia, being a nuclear weapons state, is also probably served by good relations to the Nordic-Baltic non-nuclear weapons states. Continuation of the program for destruction of nuclear war heads, using the fuel for civilian energy purposes, may also be advanced by having a visible regional energy player as mediator between the big powers.

9 Nordic-Baltic Political Attitudes

A number of official Baltic documents express desire to become an energy 'show case'. They also seem to agree on a joint nuclear energy future beyond the present Ignalina, possibly a joint venture at the Ignalina site. Focal point C deals with the present Ignalina and Baltic Perspectives.

10 Summary and Outlook

A number of countries are now considering renewal/upgrading of existing nuclear facilities and also to build new uranium based reactors. The Energy department in the US has, together with MIT, suggested building 1000 new reactors. Keep in mind that the present number worldwide is less than 500 and that many of these will have to be replaced in not too distant future, although the lifetime of the plants has been significantly extended (actually nearly doubled from 30-40 years to 60 years). This will yearly imply thousands of tons of plutonium waste and enough plutonium to build 10 000 bombs/warheads. The problems related to waste handling, transport and storage, are not solved in a generally accepted way, and such a nuclear power escalation requires parallel investments in waste handling and non-proliferation measures. A major role for sub-critical ADS installations could just be waste burning with some energy generation, and a field for Nordic/Baltic participation and Norwegian thorium fuel.

Transmutation of fertile 232Th to fissile 233U is analogous to 238U to 239Pu. Thorium fuel has however the great advantage that it produces much less radiation toxic (factor 100) high atomic mass transuranic elements (minor actinides: Pu, Am, Cm). A certain amount of 232U will always accompany the 233U production. The 232U isotope decays to elements with unusual intense and hard beta-gamma radiation. This will reduce, although not exclude proliferation, the possibility to use 233U as dirty bomb material. It also implies, however, that thorium fuel itself and its waste is more difficult to handle. Another advantage by using thorium and fast neutrons is that this allows incineration (destruction) of long-lived fission products. Inspired by Alex Bradshaw [4], we sum up some central points:

- Nuclear energy will remain an important player in the future energy composite.
- Nuclear energy may become a strong beam in our energy bridge to the future.
- The majority concerned with CO_2 worries, should be delighted - nuclear is CO_2 free!
- Nuclear has, however, its own waste challenge, but has ways ready to deal with it if allowed to try them out.
- Waste can be turned into value, stretching the nuclear fuel supply far into the future.
- Only honest scientific efforts will help us draw a reliable roadmap, not prejudice. There are, however, encouraging signs; Decision-makers seem to be finding back to better ways to communicate with the scientific community. But time is running...

We have argued for the Nordic-Baltic region as a SHOW CASE of a nuclear weapons free and proliferation safe nuclear energy supplier. The recognized Nordic role in grid development and operation, and the outspoken Baltic ambition to join the party, as well as the energy strength and variety of the region, underpin this vision.

To this end we envision a concerted effort in competence building, also joint ventures with other types of energy production/waste handling, to make the Nordic-Baltic region a visible international partner in testing, implementation and operation of new nuclear technology and science.

We foresee a future role for the Nordic-Baltic region in international advice on safety and societal aspects of nuclear energy, with experience based on a mature diversified energy composite. The Nordic-Baltic countries may also jointly achieve harmonization and energy interplay with our neighbor Russia, and become a future international mediator between Russia and Europe.

Quite a few hold the view that nuclear energy will have its renaissance in the near future. The recent publication "Double or Quits? The Global Future of Civil Nuclear Energy" (Malcolm C. Grimstone, Peter Beck. The Royal Institute of International Affairs, 2002 [9]) addresses this issue; Where does nuclear power stand nowadays and what are the conditions for a significant future role.

The quite comprehensive list of recommendations given in "Double or quits?" addresses needed actions required both by the nuclear industry and the governments, and contains: Public perceptions and decision-making; Economics; Waste, reprocessing and non-proliferation; Safety; Research, development and commercialization. From their recommendations we extract the viewgraph of actions they mean are required of the governments concerning research, development and commercialization (RD&C):

Short Term:

- Ensure that demonstration plants of those technologies close to commercial realization can be build.
- Widen the use of instruments such as tax breaks, to encourage commercial companies to increase R&D activity over a range of technological areas.
- Carry out a thorough assessment of the international potential of various longer-term options (nuclear and non-nuclear) requiring research and identify key areas for nuclear research, for example new reactor, new sources of fuel, partition and transmutation of waste.

Medium term:

- Ensure that the total resources going into global energy R,D&C are appropriate to the scale of predicted global problems over the next 50 years or so.
- Within an international context, develop a coherent portfolio approach to R&D that provides appropriate funds for the various available options.

Technology is a necessary, but not sufficient condition for a nuclear renaissance.

*While completing this report a very relevant collection of articles was published by the Latvian Institute of International Affairs; "ENERGY, Pulling the Baltic Sea Region together or apart?" [10] The Nordic Council of Ministers was the project's main financial supporter. Likewise our report, also addressing this issue, has been underpinned by support from Nordic Energy Research to Energy Forum (ECT) in Bergen.

A Nuclear Fuels: Current Resources and Future Potential - Thorium

Compared to its population, Norway is blessed with larger energy resources than most other countries. This has been important for the way of living, and also provided the country with a substantial money surplus based on energy export. Still it must be admitted that Norway has few participants, not to say movers, within most competence areas. Thus it strongly depends on international competence and collaboration, also to capitalize on its resources.

The present Norwegian competence situation hardly provides a sufficient base for Norway to take the lead in thorium related implementations; competence has to be rebuilt and extended. What may make it possible to take on the challenge of investigating future possibilities and Norwegian participation, are the networks of reliable international contacts in basic science and technology, an essential backbone today, just as it was in the days when Kjeller, the first research reactor (1951), came into being. With the large Norwegian money surplus Norway can be an international facilitator, using money derived just from energy sales. What better investment could be made than one that improves our changes for safe energy supplies and that could strengthen knowledge-based energy policy that minimizes risks for war over energy issues?

A.1 Fissile Elements

Thorium was identified in 1829 (and given name after the Norse god Thor) by the Swedish chemist Berzelius in a mineral found in 1823. The sample was found on Løvø (Lauvøya) in Langesundsfjorden near Brevik, by the Norwegian hobby mineralogist M. Thr. Esmark. We may read about this in H. Neumann's 'Norges Mineraler' Skrifter 68, Universitetsforlaget, 1985. Uranium had been discovered 40 years earlier (1789) by the German chemist Klaproth in St. Joakimsthal, and named after the newly discovered planet Uranus. A series of minerals containing uranium/thorium were discovered in Norway throughout the 19th century and given exotic names that are now history. After close to a century in radiation free ignorance, Becquerel in France discovered almost accidentally (1896) that uranium was radiating. Also Thor's element proved to spark.

Uranium makes up approximately 2 parts per million (ppm) in the Earth's crust, making it 500 times more abundant than gold, 40 times more abundant than silver and even more abundant than tin [11]. Three different uranium isotopes are found in nature: U-234 (0.0054%), U-235 (0.7204%) and U-238 (99.2742%). Of these, U-235 is the only *fissile* isotope by thermal neutrons[2]. Both U-234 and U-238 are *fertile*, but being almost 20000 times more abundant, only the latter is practical as fuel in breeder reactors. Another fissile isotope, U-233 does not appear naturally, but may be produced from thorium in reactors through the following process:

$$ {}^{232}_{90}Th + n \rightarrow {}^{233}_{90}Th \xrightarrow[21.83m]{} {}^{233}_{91}Pa + e^- + \bar{\nu}_e \xrightarrow[26.98d]{} {}^{233}_{92}U + e^- + \bar{\nu}_e \qquad (1) $$

[2] In fact U-235 is the only fissile isotope found in reasonable amounts in nature.

Natural thorium is almost in its entirety made up of the fertile Th-232 isotope,

Plutonium was first produced and detected in 1941 by Glenn T. Seaborg, Joseph W. Kennedy, and Arthur C. Wahl by bombarding U-238 with deuterons [12]. Later, some trace amounts have also been observed in nature (Pu-244). Either if used in nuclear weapons, which historically has been its main area of use, or as a part in mixed-oxide fuel (MOX), it is the fissile Pu-239 isotope which is of interest. It is made in nuclear reactors by neutron capture in U-238 and its following beta-decays:

$$^{238}_{92}U + n \rightarrow {}^{239}_{92}U \xrightarrow[23.45m]{} {}^{239}_{93}Np + e^- + \bar{\nu}_e \xrightarrow[2.35d]{} {}^{239}_{94}Pu + e^- + \bar{\nu}_e, \tag{2}$$

A.2 Uranium Resources

Current and Future Uranium Extraction: As commercial reactors today are solely being fueled by uranium, we here give a quick look at its global resources. According to the Energy Watch Group [7], which has used data from the jointly IAEA/NEA 'red book', there has as of 2006 been extracted 2.3 million tonnes uranium. Annual production in 2008 was 42 000 tonnes, while the supply was 67 000 tonnes. The rest of the demand comes from earlier stockpiles, built up prior to 1990. During the first decades after the second world war the uranium production was strongly driven by military use [7]. This resulted in the first peak around 1960 (as seen in Fig. 8), which was mainly due to the arms race during the cold war.

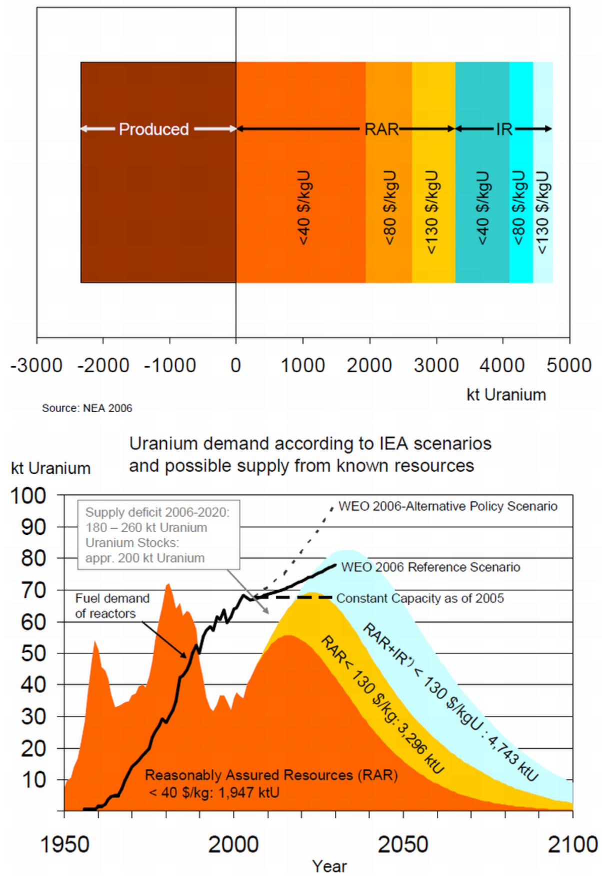

Fig. 8: Produced, Reasonably Assured Resources (RAR) and Inferred Resources (IR) of uranium. Fuel demand and projections [7]

After a fall in production in the 80's (cheap oil) until around 1990, the annual production has had a slight increase the later years. The current production is about two thirds that of the annual fuel demand, which means that a significant increase is needed if production is to equal demand, even if the capacity is kept constant. The reference scenario given by the World Energy Outlook (WEO) in 2006 estimated an increase in fuel demand by around 15% by 2030. As seen in Fig. 8, including the costlier, reasonably assured resources, and furthermore inferred resources, the peak production of uranium is displaced by ten years each, with the full scenario giving an estimated peak in 2035.

Logically, sites with the highest ore content are mined out first. Today only Canada have reasonable amounts of high ore-grade (larger than 1%). Most countries only have mines with an ore grade below 0.1% and two thirds only have concentrations below 0.06% [7]. Together with Australia and Kazakhstan, Canada has the largest reserves of cheap uranium (below 40 \$/kgU), as can be seen in Fig 9. From the same figure it is seen that several countries have already fully exploited their national uranium resources, including Germany and France, the latter being the second largest producer of nuclear power in the world.

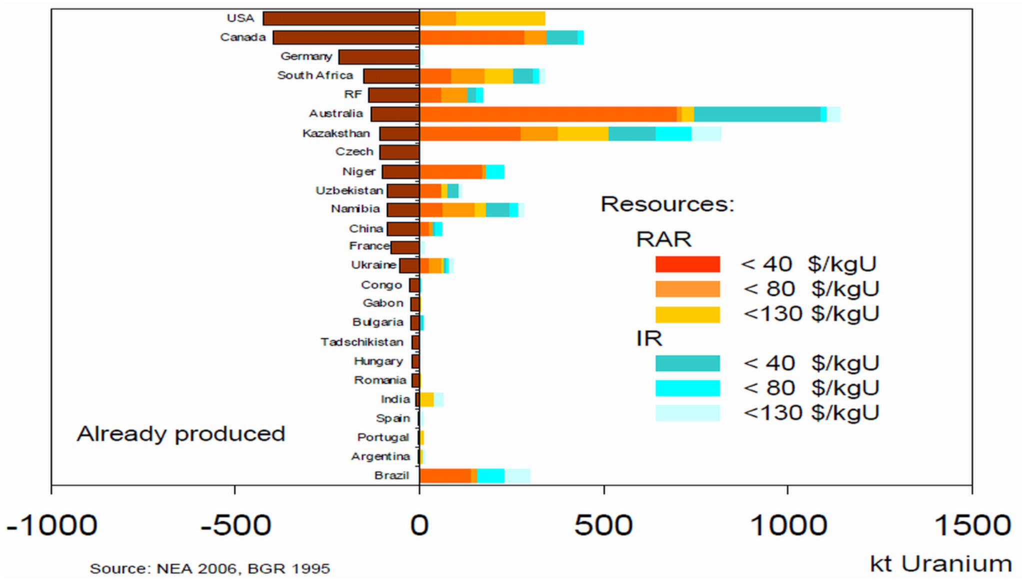

Fig. 9: Produced and remaining uranium by country

Uranium from Decommissioned Nuclear Weapons: In 1993 the U.S. and Russia agreed on a program to convert highly enriched uranium (HEU) from nuclear warheads to low enriched uranium (LEU) usable as nuclear fuel, the so-called "Megawatts for Megatons" project. By December 2008, more than 14000 warheads had been dismantled [13]; 352 tonnes of weapons grade uranium (HEU) had been converted to 10213 tonnes of LEU, which is equivalent to around 100000 tonnes of natural uranium. When the program is ended in 2013, 500 tonnes of Russian HEU will have been converted to nuclear fuel. This amount is enough to cover the global fuel demand for two full years.

In 2000 the same two countries agreed to dispose of 34 tonnes of weapons grade plutonium. This is either to be immobilized or to be used as MOX-fuel (Mixed OXide fuel) [14]. It should however be noted that the uranium and plutonium used in these weapons are not a new source of uranium as they are already included in the data for the extracted resource.

Unconventional Resources:

Seawater: An estimated 4 billion tonnes of uranium is found in seawater, roughly two thousand times the amount of produced uranium as of today. The concentration is, however, very low: 3.3 ppb[3]. According to the Analytical Center for Non-proliferation [15], the cost of extracting uranium directly from seawater would be between five and ten times that of land based uranium mining (as of 2004). The technology has only been tested on a laboratory scale.

Phosphates: According to the World Nuclear Organization (WNA) there are 22 million tonnes of uranium in phosphate deposits [16]. Although in a low concentration (estimated at 100ppm), this uranium can be extracted as a by-product from the phosphate needed in agriculture.

Uraniferous Coal Ash: In China there has been a project involving uraniferous coal ash. By extracting the uranium from the ashes from coal power stations, the group indicated a concentration of around 160 ppm uranium [17]. The global reserves of coal is estimated at around 1 trillion tonnes[4] [18].

A.3 Reprocessing, Closed Fuel Cycles and Radioactive Waste

In a thermal reactors more than 95% of the spent fuel is U-238. There is also a fair amount of U-235 left, and new Pu-239 which has been bread from U-238. With a closed fuel cycle the spent fuel is sent to reprocessing after it has cooled down. There the fuel elements are cut and dissolved in nitric acid (HNO_3). The resulting solution then undergoes solvent extraction and ion exchange steps to separate the elements [19]. The reprocessing is chemically easy, but because of the harsh radioactivity of the elements, the technical process is difficult and remote handling is needed.

The storage time for the radioactive waste depends on the elements and material. Radioactive waste is categorized in three levels: Low level waste (LLW), medium level waste and high level waste (HLW). When it comes to a nuclear reactor; the spent fuel is HLW, while the other components of the reactor are considered MLW or LLW depending on the exposure of radiation. The rules concerning LLW and MLW are not as strict as HLW, and these need less shielding and storage time.

The reprocessed uranium and plutonium can then be used as new fuel. The rest products are all sent to permanent storage or separated. The remains of the chopped off fuel rods can be stored as medium level waste (MLW), while the rest products from the spent fuel consisting of minor actinides (MA) and fission products (FP) are stored as HLW. In ADS and some generation IV reactors the MAs may be stacked in separate rods, or as a mixture in the fuel rods, and put into the reactor in order to burn them through fission.

[3] ppb = Parts Per Billion. (3.3 ppb = 3.3 grams of uranium per m^3 of water)
[4] Fresh coal, not coal ashes.

The incineration of a MA requires fast neutrons at high fluxes, as only a small fraction of MA isotopes are fissile. Several neutron captures might be necessary before a fission reaction occurs. When extracted from the reactor, the MA-rods are again reprocessed, separating the FA and MA.

Untreated high level waste from reactors will stay highly radioactive for a long time, and will be dangerous for hundreds of thousands of years [20]. From a storage point of view it might therefore favorable to use the aforementioned reprocessing methods as much as possible.

A.4 Mixed Fuel

Many of today's reactor either use or have the possibility to use a mix of different fuels. MOX (Mixed OXide) fuel is a mixture of different kinds of uranium and plutonium oxides. The most common mixture is (U, Pu)O_2, originating either from nuclear warheads or reprocessed from spent fuel. The latter is also called PUREX, an acronym for Plutonium - URanium EXtraction. Thorium can be mixed with both uranium (Th, U)O_2 and plutonium (Th, Pu)O_2. Even though the two latter oxides are mixed fuels, it is common to refer to them as thorium-uranium and thorium-plutonium instead of MOX to avoid being confused with the uranium-plutonium mixture.

Since thorium is not fissile, pure thorium cannot be used as a fuel when the reactor starts up. Normally this would be solved by using U-235 in the start-up period. After a while the reactor will breed its own fissile material, U-233, from the thorium. So future fuel can in principle just consist of Th-232.

A.5 Benefits of Using Thorium Fuel

Thorium has been used in fuel, as thorium uranium mix in several experiments, starting in the mid-50's and lasting for roughly three decades. All projects regarding the thorium fuel cycle were terminated in the 80's [5]. The IAEA report: "Thorium fuel cycle - Potential benefits and challenges" [21] states that the reason why the thorium fuel cycle has not been introduced commercially is that, at the moment, the uranium resources are sufficient. Underlying here is the fact that it is cheaper to run a reactor on the already established and well-known uranium cycle.

The view by the Norwegian Thorium Report Committee is that the thorium cycle projects were abandoned in the 80's for three reasons [5]:

1. The thorium fuel cycle could not compete economically with the more well-known uranium cycle.
2. In many countries there was a lack of political support for the development of nuclear technology in the aftermath of the Chernobyl accident.
3. An increased worldwide concern regarding the proliferation risk associated with the reprocessing of spent fuel.

In the latter years there has been increased interest in the use of thorium because of several interesting qualities. The IAEA lists the following 5 properties as reasons to consider thorium [21]:

Intrinsic Proliferation: As a bomb-material pure U-233 is theoretically very suitable. There are however some practical problems. First of all there will always be U-232 present in thorium reactors. U-232 is formed by U-233(n,2n)U-232. The U-232 has a short half-life of 69 years and has strong gamma emitting daughter products. From a weapons point of view this is undesirable because it can cause a pre-initiation of the bomb. The presence of U-232 also makes it difficult to fabricate weapons grade U-233 because of the harsh radiation environment. While the protection needed to handle U-235 and Pu-239 is gloves and a suit, the U-232 and U-233 has to be handled remotely. Separation of U-233 from U-232 is also more difficult because of the small difference in mass of the two.

Still, the aforementioned arguments do not exclude the construction of a nuclear bomb based on the U-233-isotope. Less than a third of the mass compared to U-235 is needed, and about 60% more than that of Pu-239 [22]. But there is no doubt that the effort needed, by far disfavors U-233 compared to the other alternatives.

Better Thermo-physical Properties: The chemical properties of ThO_2 has some promising features compared to those of UO_2. First off, it is more stable and has a higher melting point. The amount of fission products which escapes the confinement of the fuel rods, the so-called fission product release rate, for ThO_2 is one order of magnitude smaller than that of UO_2 [21]. Other advantages of ThO_2 are higher thermal conductivity and radiation resistance.

Fewer Long Lived Actinides: The use of ThO_2 fuel hardly produces any minor actinides (Np, Am, Cm) or plutonium. The U-233 isotope has to capture neutrons all the way to U-237 before it has any real chance of beta-decaying to Neptunium. And on this way, fission has to be avoided in the fissile isotopes, U-233 and U-235. The reduction of long-lived high atomic mass minor actinides in the thorium fuel makes it favorable compared to uranium and U-Pu (PUREX) fuel concerning long-term nuclear waste. There are however, other unwanted elements connected with thorium fuel, e.g. Th-228, Th-229, U-230, Pa-231, and U-232 [21], as well as the fission products.

Superior Plutonium Incineration: In regard to plutonium incineration, it is much better to do so using (Th, Pu)O_2 fuel, compared to (U, Pu)O_2 fuel, as the former does not breed any additional plutonium. By incinerating plutonium in normal uranium reactors, the U-238 isotope which is always present can be bred into plutonium itself.

Attractive for Use in Accelerator Driven Systems (ADS): Based on the above discussion, thorium seems like a good candidate for accelerator driven systems (ADS). As one of the objectives of ADS is the transmutation of actinides, the use of thorium seems beneficial since the thorium virtually does not produce any TUE itself.

'There will come a time when the oil in the lamps of the lighthouses will be replaced by the power in the stones I hold in my hand. Great things will happen. The uranium-cleveite contains mighty forces'. People smiled when the aging thorium pioneer Kartevold a century ago voiced his visions, inspired by the international community he had chance to make contact with and even meet during his years as owner of Thors Grube (mine), in Vats in Western Norway. Fifty years later, many also doubted that the fission pioneers at Kjeller would get anywhere. Still twenty-five years later few could envision Norway's present competence in petroleum technology. Things take time - even if the money is present - all development requires believers who are able to fight the status quo preserving forces that Machiavelli describes so well. Often competence that was developed for different reasons and purposes becomes crucial. Thus Norway's World dominance in seismic exploration has its roots in a small group in Bergen that worked on monitoring Russian atomic bomb explosions.

The enthusiasm for getting going with thorium has sparked off some apparent controversies reflecting divided opinions about what comes first. Recently this again surfaced in a News bulletin in the journal *Physics World* informing us that the US firm Thorium Power in collaboration with the Russian Kurchatov Institute are optimistically under way with the Radowsky-type thorium reactor concept based on conventional Russian VVER-1000 reactors. In a comment to this news release one of the spokesmen for the ADS variant, questions the time estimate of a decade or so for the Radowsky solution, and states that he believes that the realization of ADS is closer in time if investments are made. In our opinion both lines of development should be pursued - and probably will. The question for Norway and the Nordic/Baltic area is if we are going to be part of the venture.

A.6 Nuclear Properties of Thorium-232 and Uranium-233

> "^{233}U is by far the best 'fissile' isotope for thermal neutron spectrum and can be used for breeding in both thermal and fast reactors".

The above quotation is from the 2005 IAEA report: Thorium fuel cycle - Potential benefits and challenges" [21], and indeed the nuclear characteristics of Th-232 and U-233 are good. First of all, as can be seen in Fig. 10, Th-232 has a higher cross section for neutron capture, $\sigma_{n\gamma}$, compared to that of U-238. This makes the breeding process of Th-232 $\rightarrow$ U-233 more efficient than the U-238 $\rightarrow$ Pu-239, even though the resonance spectrum of U-238 is three times bigger than that of Th-232.

The fissile U-233 has a very good neutron yield when it absorbes neutrons, with η being above 2 for a wide range of the neutron energy spectrum. And, as can be seen from Fig. 10, the U-233 has much better neutron yield in the thermal energy spectrum than its two counterparts, U-235 and Pu-239. Keeping η above 2 is essential for breeding, as for every fission one neutron has to hit another fissile nuclei, thus keeping the chain reaction going, and at least one other neutron to be absorbed in a fertile nuclei, thus keeping the fissile fuel constant or increasing. The capture and fission cross section for thermal energies is given in Tab. 1 [21]. For U-233 this means that one in every eleventh thermal neutron

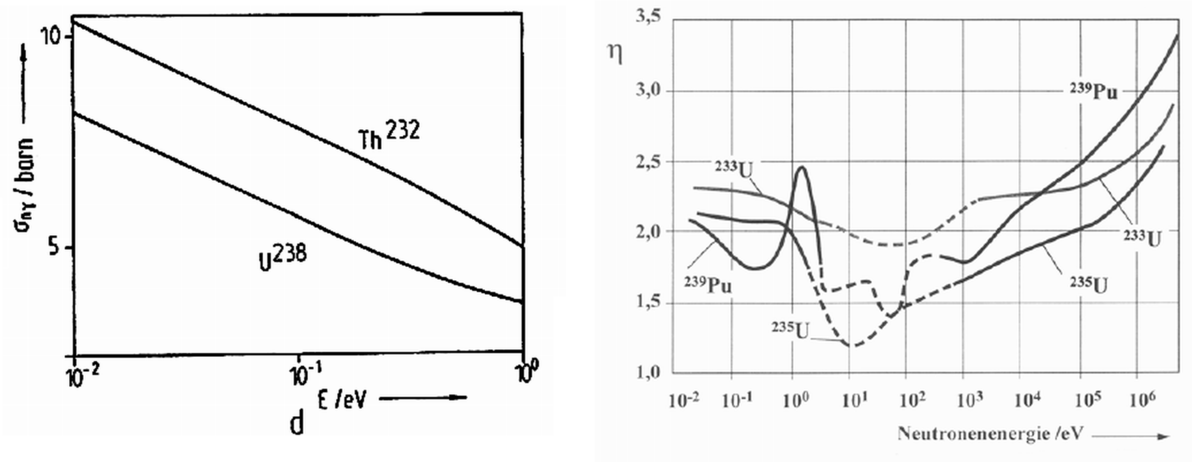

Fig. 10: Left: Neutron capture cross section $\sigma_{n\gamma}$ of thermal Th-232 and U-238 [23]. Right: Neutrons released, η, for U-233, U-235, Pu-239

absorbed will lead to a heavier isotope instead of fission. This is twice as efficient as for U-235 and four times as efficient as for Pu-239, making it better from a recycling point of view as well.

Isotope	$\sigma_{n\gamma}$ (Capture)	σ_f (Fission)
U-233	46 b	525 b
U-235	101 b	577 b
Pu-239	271 b	742 b

Tab. 1: Capture and fission cross sections for U-233, U-235, and Pu-239.

A.7 Norwegian and Global Resources of Thorium

Thorium is a quite abundant element, with an average concentration of 10 ppm in the Earth's crust [21]. This makes it around three times as abundant as uranium, and as abundant as lead. Thorium is found in many minerals, of which monazite is the most important. Monazite is a phosphate containing rare earth elements, with two thirds of the worlds resource located in India.

A global reserve is estimated to be around 1.4 million tonnes, with an additional 1.2 million tonnes of reserve base (resources). The largest reserves are found in Australia, India and Norway. Including the reasonably assured resources (RAR) and inferred resources (IR) will add another 2.23 million and 2.13 million tonnes respectably [21]. For the Norwegian situation the numbers are an additional 132000 tonnes for both RAR and IR.

The current thorium production is limited, being almost entirely a by-product from extraction of rare earth elements (REE)[5] in monazite sand.

[5] The rare earth elements consist of scandium, yttrium, and the fifteen lanthanoids (Atomic numbers

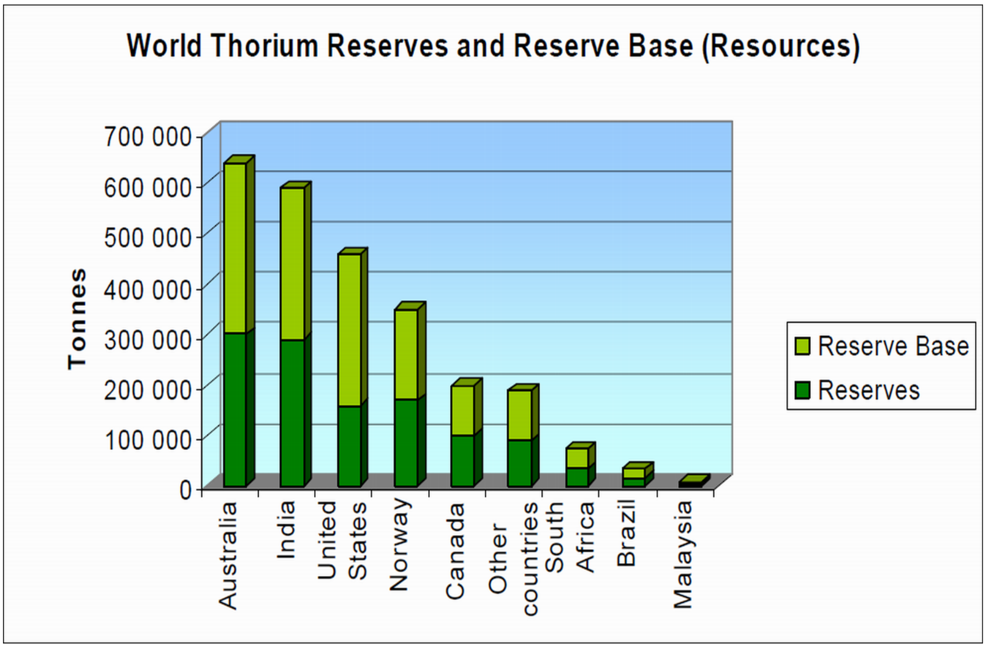

Fig. 11: Global Reserves and Resources of Thorium.

A.8 Nuclear Activity in Norway

The Norwegian experience starts back in post-war 1945 when the young astro-physisist Gunnar Randers was chosen to lead a committee to investigate the possibilities for nuclear activities in Norway. Together with the experienced accelerator builder Odd Dahl and the central politician Jens Christian Hauge an initiative was taken and the Institute For Atomic energy (IFA) was established in 1948. Thus already in 1951, Norway had its first research reactor, the JEEP-I[6] reactor at Kjeller. A second research reactor was built in Halden, and was operational in 1959 [24]. After the government in 1979 decided to neglect nuclear power as an opportunity for Norway for the next 20 years, IFA changed their name to "Institutt for Energiteknikk" (IFE) in 1980.

Today IFE operates both the research reactors at Kjeller and Halden, the only nuclear reactors in Norway, with a turnover of NOK 533.5 million in 2006 [25].

Kjeller: The JEEP reactor, located at Kjeller outside of Lillestrøm, went critical on its first try in 1951. It was replaced in 1967 by the JEEP-II reactor, a 2 MW_{th} reactor, using heavy water (D_2O) as both moderator and coolant. The fuel consists of 250 kg low enriched uranium (LEU) in the form of UO_2. The JEEP-II reactor is used as a neutron source, with the three primary tasks being production of radioisotope production, basic scientific research in physics and radiation of materials for technical and industrial needs [26].

57-71).

[6] Joint Establishment Experimental Pile

Halden: After a decision in 1954, IFA began the construction of a new reactor in Halden, the Halden Boiling Water Reactor (HBWR) in 1955 [24]. It was built inside the mountain next to the river Tista and was operational in 1959. At the time only natural uranium was commercially available, so heavy water had to be used as moderator. The heavy water was produced by Norsk Hydro at Rjukan. In 1958 IFA and OEEC (the precursor of OECD) signed an agreement for international research at Halden - The Halden project.

The HBWR has a maximum output of a 25 MW_{th} and uses 14 tons of heavy water for both coolant and moderator. The operational temperature is 240°C. The core has between 110 and 120 fuel assemblies and is versatile when it comes to fuel and materials. The main focus of the HBWR research reactor is advanced studies on fuel and core materials and reactor safety[27].

Fig. 12: From the left: Gunnar Randers, HM King Olav V, Odd Dahl and Major Arne Haugli. Photo: IFE

B Carbon and Radioactive Waste Storage

B.1 Radioactive Waste Storage and CO_2 Storage

When comparing radioactive waste and CO_2 several similarities are apparent. Both originate in the crust of the earth and have since been processed such that they are undesirable and harmful at surface level. The plan is in both cases to put the waste back in the ground. It is then natural to explore how one can learn from the other. We will also see that lessons from thermal power generation are useful in this respect.

B.2 Generalist Models

A model of a physical system implies some simplifications of the processes involved to make the whole process understandable and possible to simulate. Since radioactive waste and CO_2 storage have a high degree of similarity one may, however, leave enough parameters open in a model to make it applicable for both problems.

B.3 Open Systems and Fluid Loss

Experiments for developing *Hot Dry Rock*, HDR, systems started in the 1970's in Los Alamos National Laboratory (LANL). Numerous tests have since been performed in the US, Japan, Germany, France and England. Notably a German-French project at Soulz, France which started in 1986, achieved $8MW$ of thermal power production in 1994-1995 and $11MW$ of thermal power over a four month testing period in 1996 at $3876m$ depth. A German project at Urach (Germany) which started in 1975 reached a depth of $4445m$ in 1997 [28].

There have, however, not yet been any commercially successful attempts with this method. One recurring problem is the loss of working fluid (water) due to the porosity of the crust. In practice, a continuous flow of water has to be supplied from external sources to counteract this loss.

B.4 CO_2 as an Alternative Working Fluid

A recent simulation by Karsten Pruess at Lawrence Berkeley National Laboratory [29] indicates that CO_2 may work just as well as water, and even have a number of advantages as working fluid in geothermal energy production.

B.5 Carbon Storage and Geothermal Energy

Carbon storage could become a bi-product of geothermal energy production. Further, one could combine it with fossil powered plants, thus creating a CO_2 neutral source of energy where both the production and disposal of CO_2 are profitable segments.

B.6 Modelling, Simulation and Experimentation

It is clearly important to assess the durability, capacity and stability of such storage. This must, in the first instance, be done via models and simulations.

B.7 Two Birds With one Stone

From a general model one can develop a general simulator that allows arbitrary material properties to be input for each simulation run. Two problems may then be solved via the same effort: 1) CO_2 neutral energy and 2) safe disposal of radioactive waste.

C Nuclear Energy Perspectives in the Baltic States

Although the three Baltic States have quite different energy profiles, they share a common historical interdependence along with extremely high degree of dependence on Russian energy supplies that will be further aggravated by the closure of the Ignalina NPP, the mainstay of the region's electricity supply, by 2010. A number of studies show that regionally integrated energy policies and investments are the most efficient and cost-effective approach meeting the Baltic region's future energy needs, enhanced supply security and diversification. In a broader extent, to meet these goals the connection of the Baltic region to the Nordic and Polish energy grids became an urgent and indispensible "must".

Commissioning of the 350 MW electricity grind line (jointly financed by the three Baltic States) and a firm decision to build a new one of the same capacity between Estonia and Finland (2006) opens the 1^{st} opportunity window for future integration of Baltic and EU/Nordic energy markets. Recently, a long awaited political agreement has been reached to interconnect Lithuania and Sweden with a new 1000 MW capacity line, again commonly supported by the Baltics and co-financed by the EU. Finally, the interconnector between Lithuania and Poland is equally in the EU high priority strategy plan with a very strong political support of both countries, will most probably be operational in 2012-2013. This shows that after many years of visible stagnation of construction of transport capacities the new period of renovation and modernization has come.

Natural gas will continue to be one of the primary energy sources in the nearest future, and the Baltic countries are investigating various possibilities to reduce risks of entire reliance on a single supplier, namely Russian Federation. The same is valid for the provision of the nuclear fuel at Ignalina NPP, the closure of which by the end of 2009 obliges the three Baltic States and Lithuania in particular to promote utilization of renewable energy sources in combination with full liberalization of the energy markets. This situation equally pushes for a strongly diversified energy imports for building up a new environment for future developments, so the present single-supplier situation will remain an historical lesson, learned although with some delay.

Indeed, the governments of the three Baltic States decided jointly to start the preparation for construction of a new NPP with completion in 2018-2019. In 2008 Poland has joint the common initiative, resulting in the final targeted capacity of 3000MW electric. The environmental impact assessment has been finalized confirming feasibility of such a future plant. Recently, a creation of the Ministry of Energy by the government of Lithuania hopefully will place this extremely important project into the priority "must do" list both in the context of national and regional strategies.

The future needs and place for nuclear power in the Baltic/Nordic region countries, including Poland, where their geographical positions and the diversity of the existing energy systems retain a remarkable potential for enhanced cooperation in that part of Europe. Successful cooperation, stimulated by geographical base and old historical traditions, must comprise the involvement not only of economical but also political, research and development actors. The Baltic Sea region is the region of very high concentration of research and development institutions and facilities for energy applications, and time has come to use this remarkable potential in energy sector, where nuclear energy will certainly preserve, if not increase, its respectful place in the years to come.[30] [31]

D Our Civilization's Dependence on Nuclear Energy

D.1 Energy Sources and Connections to Nuclear Reactions

Solar Power

The electromagnetic energy radiated from the Sun provides light and heat, but is also used widely for electricity generation. This is usually done via photovoltaic solar panels, or via solar thermal collectors[7], but can also be done in a multitude of other ways.

The solar radiation has its origin in nuclear reactions occurring in the Sun. More specifically: from the fusion of hydrogen into helium. This energy, released from nuclear interactions, is several orders of magnitude greater than energy from any chemical reaction.

Geothermal Energy

Geothermal energy is in practice the heat energy in the crust of the Earth, which in present time is utilized for heating and electricity generation in geologically suitable areas. This is replenished by the decay of radioactive elements in the crust and deeper down towards the core of the Earth; so-called natural radioactivity which stems from the star dust from which the Earth was formed. This is not a chain reaction like the fusion in stars or the fission in nuclear power plants. But nevertheless it is a form of nuclear energy. Exactly how much of the heat is currently replenished by radioactivity is not known though. The ratio of radioactive energy output to total energy output of the planet is called the *Urey ratio* and estimates vary from 0.4 - 0.85 [32]. As time passes, less radioactive elements remain, so the Urey ratio is not as high now as it was when the Earth was younger.

Weather Driven Sources

We tap into the weather systems on Earth and use it to generate energy in a multitude of ways. Wind turbines are used to generate electricity. Rain or melting water is collected in dams on mountains and used for hydroelectric power generation. There are examples of converting the motion of ocean waves into electric energy (with varying degrees of success). Not yet realized possibilities of using osmotic pressure at large river mouths also exist. Three things underpin the weather system on Earth: Tidal forces, geothermal energy, and electromagnetic radiation from the Sun. Tidal forces are not nuclear in origin but only accounts for a tiny fraction of the total. Solar radiation and geothermal energy, however, are as we have seen nuclear in origin. So except from the small fraction that comes from tidal energy, the weather system on Earth, and thus the energy we get from it, is a consequence of nuclear reactions occurring inside the Earth and inside the Sun.

[7] Solar thermal collectors intensify the solar radiation with focusing mirrors in order to heat a medium, which again is used to drive a steam turbine.

Biofuels and Fossil Fuels

As the weather system on Earth is driven by the Sun, so is almost all biological life we know of. Plants use the energy from the Sun directly for photosynthesis and animals use the chemical energy contained in the plants. Fossil fuels and biofuels both originate in plant life. The difference between the two is that for fossil fuels the biological matter has been naturally converted into hydrocarbons over long time and under high pressure, whereas for the biofuels we actively process biological material into hydrocarbon based fuel. But they are both, as the weather driven sources, ultimately dependent on the nuclear reactions in the Sun.

Nuclear Power Plants

The relation to nuclear reactions is here fairly obvious, both in the sense that the relation is very direct, and in the sense that this type of power generation became possible as a result of our understanding of the nucleus, and the discovery of fission (1939). A nuclear reactor is together with geothermal energy the most direct utilization of nuclear reactions for energy production. Reactor produced energy has a high degree of similarity to geothermal energy. In both cases the nuclear reaction creates heat, which in turn is used to run a steam turbine to generate electricity.[8] What makes nuclear power plants special is that the nuclear reactions which generate the heat energy are artificially created and controlled chain reactions.

D.2 Categorizing Sources of Energy

Renewable

The Sun may be considered as an infinite energy source, something which is not strictly correct, but for now the energy it contains is so vast that it might as well be considered infinite. If we now define a renewable energy source as an energy source which is renewed at the same rate as we consume it, then it is clear that solar power and weather driven systems fall under the category of renewable energy. Biofuels are also in this category if the agriculture they are based on is also renewable (i.e. that is does not use any resources which are not renewed at the same rate as they are consumed). Geothermal energy is a special case. If we consider the total energy, both in form of heat and in form of nuclear potential which is stored in planet Earth, it is very large. Though, not near the same magnitude as for the Sun, we might consider it infinite if compared to our current needs. However, as we only have access to a small volume in the order of several kilometers of depth we are limited by the thermal conductivity of the crust. If heat is tapped from a small area faster than heat can be conducted from elsewhere the heat will eventually be depleted. This is largely the case for geothermal energy today. So geothermal energy is not renewable at present time, but it has the potential to become renewable.

[8] In the geothermal case the heat might be directly used (locally) if energy in form of heat is desired.

CO_2 Producing (fossil)

CO_2 producing energy is energy stored in geological deposits which release CO_2 to the atmosphere when burned. That is, fossil fuels like coal, oil and gas. From now on this will simply be referred to as fossil fuels. Other types of energy production might also indirectly contribute to CO_2 emissions, for example in production and transportation. But that is a matter of choice, if one has the capability to produce CO_2 neutral energy one can choose to use this for the entire process. There are also energy sources that emit CO_2 but do not contribute to a net increase in CO_2 levels because an equal amount is consumed in production (e.g. biofuels).

Alternate

The category of alternate energy contains energy which is not renewable, but which is CO_2 neutral. Of the different kinds of energy production already mentioned, nuclear power plants are dependent on fissile material which exist in a limited amount, so in their present mode of operation they fall into this category. Breeder reactors would however extend the fuel supply by several orders of magnitude as they do not rely only on fissile material but can also utilize fertile material like thorium-232 and uranium-238. Also, if fusion power plants become a reality they will not fall into the alternate category because the fuel (deuterium and tritium) exists (or may be produced) in such amounts that it might be considered infinite. But since one has not yet been able to generate any usable surplus of energy from artificial fusion, present day nuclear power plants are non-renewable. Traditional geothermal energy production is dependent on a reservoir of heat or groundwater, so it too falls into the alternate category.

D.3 Historical Development

To make predictions about future development it can be useful to take a look at the past. The following graphs (Fig.13) show the ratios of renewable, alternate and fossil fuels, and how they have changed, from 1965 to 2007.[9]

Fig. 13 shows that the fraction of fossil fuels has decreased slowly between 1970 and 2000 followed by a slight increase until 2007. Interestingly, the fraction of fossil fuels seems to be more correlated to the alternate sources than to the renewable sources.

We can describe correlations in more detail by calculating the *correlation coefficient*.[10] The calculation yields the following results

[9] Historical data used to produce the graphs are from [33].

[10] The correlation coefficient, ρ, is a dimensionless quantity constructed from two datasets, ranging from -1 to 1. $|\rho|$ is the strength of the correlation, and the sign is the direction of the correlation. If $|\rho| = 1$ it indicates that the two datasets are proportional, whereas $\rho = 0$ indicates that there is no mutual influence between the two datasets.

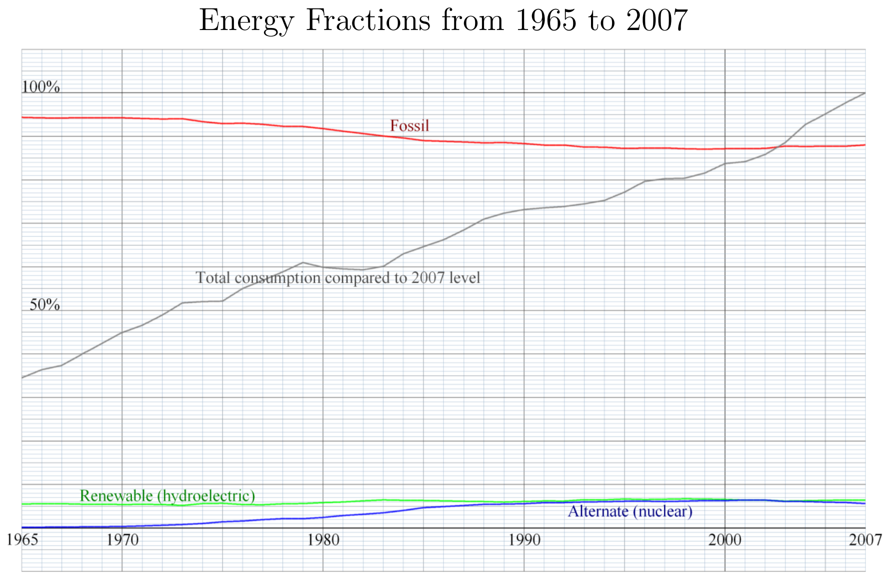

Fig. 13: The graphs show the fraction of the respective categories compared to total. Though the categories of alternate and renewable include a broader variety of production they have been up to present time completely dominated by nuclear and hydroelectric energy, as indicated by the labels. The rise in total consumption is also given.

Categories	correlation
Fossil-renewable	$\rho_{f,r} = -0.909175$
Fossil-alternate	$\rho_{f,a} = -0.973842$
Renewable-alternate	$\rho_{r,a} = 0.882347$

Not surprisingly we find that all the fractions are strongly correlated, as they all necessarily must sum up to 100%. However, as indicated by visual inspection of the graphs in Fig.13, the correlation between fossil fuels and alternate sources is particularly strong. In fact, it is almost linear.

Fig.14, which gives the increase of the three categories up to 2007, clearly shows that even though the fraction of fossil fuels relative to the other categories has decreased, the consumption of all the categories has increased because of the increased total consumption. It is also interesting to observe that though the consumption of renewable sources has increased more rapidly the last years, the consumption of fossil fuels also has a sharp increase which can only be explained by the correlated decrease of alternate fuels. It is clear that the reduced fraction of nuclear power from 2000 to 2007 has come at the expense of increased CO_2 emissions.

D.4 Future Projections

If it is assumed that the current level of CO_2 emissions lead to undesirable climate changes, we must be more interested in the total volume than in the fraction of fossil fuels to other

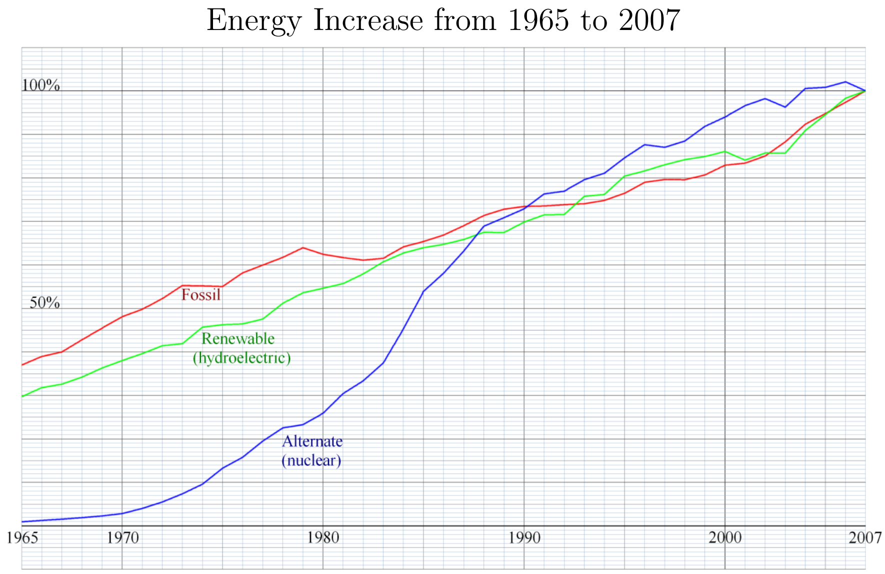

Fig. 14: The graphs show the consumption of the respective categories compared to 2007 level.

sources. So to prevent or reduce the climate change we wish to reduce the amount of fossil fuels compared to the present unacceptable level.

In addition, as a safeguard from depletion of our energy resources, we would also like to have a certain percentage of the total consumption come from renewable sources. This percentage should be high enough, so that if the non-renewable sources run dry, we will have something to fall back on. Ideally the increase in renewable sources should replace the decrease of fossil fuels consumption. But because the total need for energy in all likelihood will increase, and limitations on how much we can increase renewable energy sources the alternate category must be increased as well. Below we will look at example scenarios before presenting our analysis more precisely in mathematical terms.

Scenario I Using the 2007 consumption level and distribution as reference, let us consider decreasing the amount of fossil fuel consumption by 30%. Furthermore, we increase the renewable energy sources so that it contributes 49% of our new total energy consumption. Now we can examine how the need for alternate sources increases with the increase of total energy consumption.

Fig. 15 shows that at a total consumption increase below 21% no alternate sources would be needed if the scenario conditions were to be met. If the total consumption increases beyond 32% however, the alternate sources will also have to be increased to compensate.

Scenario II In all likelihood it will be impossible to increase the renewable energy ratio to an arbitrary level. If we consider a 30% reduction of the fossil fuels most important, we

Alternate Energy vs. Total

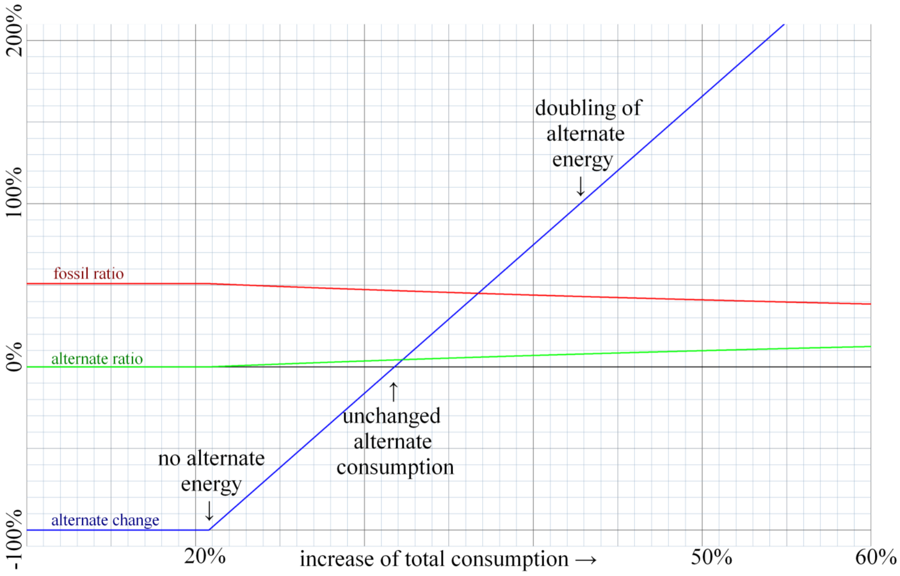

Fig. 15: The percentage of alternate increase is relative to 2007 level.

can then examine how an increase in alternate sources can compensate for a lower increase ratio of renewable sources.

Alternate Energy vs. Renewable

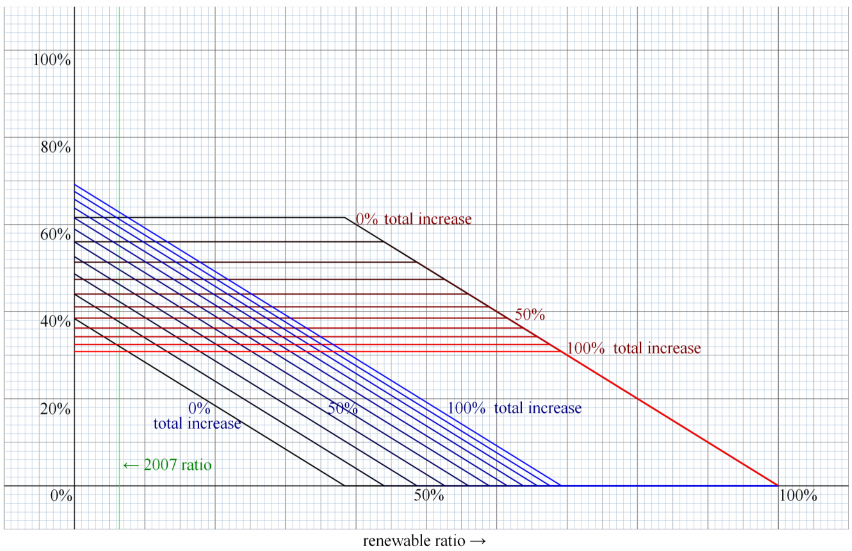

Fig. 16: Ratio of alternate and fossil fuels versus ratio of renewable sources. The red gradients are fossil fuels, and the blue gradients are the alternate sources. The darkest graphs assume no change in total energy consumption and the brightest assume 100% increase in total consumption.

Fig. 16 shows that the renewable sources could completely replace the alternate sources if increased from today's 6.4% to between 38% and 66% of total depending on the increase of total consumption. However, if we could get in the position where a decrease of alternate fuels was possible, it might make more sense to further decrease the fossil fuels instead. This would make sense from a climate perspective as well as lowering our dependence on non renewable sources (as fossil fuels also are non-renewable). Of course alternate sources might also contribute to pollution. For example in the form of nuclear waste, either from accidents or improper disposal. So this risk must be weighed against the risks of climate change.

Mathematical Relations The above graphs are made from the simple principle that the energy from all the categories must sum up to the total consumption. From the mathematical point of view, we can set up a few relations which will clearly show how the three sources relate to each other. We name the current consumption T_0, F_0, R_0 and A_0 (total, fossil, renewable and alternate), and the future consumption T_1, F_1, R_1 and A_1. The volume quantities in the future and now can be expressed in terms of each other by the following relations

$$\begin{aligned} T_1 &= T_0(1+p_T) \\ F_1 &= F_0(1+p_F) \\ R_1 &= R_0(1+p_R) \\ A_1 &= A_0(1+p_A) \end{aligned} \tag{3}$$

Here p_T, p_F, p_R and p_A give the increase of total, fossil, renewable and alternate respectively. That is, if we would have a 30% decrease of fossil fuels, for example, then $p_F = -0.3$. The parts must all sum up to the total, i.e.

$$\begin{aligned} T_0 &= F_0 + R_0 + A_0 \\ T_1 &= F_1 + R_1 + A_1 \end{aligned} \tag{4}$$

We are interested in the relations between increase/decrease of the various categories, so we rewrite the equations in the following manner

$$T_1 = F_0(1+p_F) + R_0(1+p_R) + A_0(1+p_A)$$

$$T_1 = T_0 + p_F F_0 + p_R R_0 + p_A A_0 = T_0(1+p_T)$$
$$\frac{T_0}{T_0} + p_F\frac{F_0}{T_0} + p_R\frac{R_0}{T_0} + p_A\frac{A_0}{T_0} = \frac{T_0}{T_0}(1+p_T)$$

This results in the following equation

$$p_T = p_F\frac{F_0}{T_0} + p_R\frac{R_0}{T_0} + p_A\frac{A_0}{T_0} \tag{5}$$

The fractions are simply the start ratios to the total consumption in the various categories. If we use global 2007 numbers [33] we have[11]

$$\frac{F_0}{T_0} = \frac{9768.0Mtoe}{11099.3Mtoe} \approx 0.880\ (88\%)$$
$$\frac{R_0}{T_0} = \frac{709.2Mtoe}{11099.3Mtoe} \approx 0.064\ (6.4\%)$$
$$\frac{A_0}{T_0} = \frac{622.0Mtoe}{11099.3Mtoe} \approx 0.056\ (5.6\%)$$

Putting these numbers in the above equation gives

$$p_T = 0.88p_F + 0.064p_R + 0.056p_A \tag{6}$$

We see that the coefficient in front of p_F is more than 10 times greater than those of p_R and p_A. The consequences of these numbers are as follows: If one wish to reduce CO_2 emitting fossil fuel consumption this has to be coupled with much higher rates of increase of alternate or renewable sources. Making the change as quickly as possible can be more easily achieved by an increase of *both* alternate and renewable sources because that requires less increase in each category.

As discussed earlier, for the renewable sources we might be more interested in how much it will contribute to our total supply instead of how much we have to increase it. So we might decide that a certain fraction, call it r_1, of our total energy consumption in the future shall come from renewable sources. What will then the increase, p_R, be?

$$r_1 = \frac{R_1}{T_1} = \frac{R_0(1+p_R)}{T_0(1+p_T)} \tag{7}$$

Solving this for p_R we get

$$p_R = r_1\frac{1+p_T}{R_0/T_0} - 1 = r_1\frac{1+p_T}{0.064} - 1 \tag{8}$$

From Eq.(8) we can determine if the desired ratio of renewables is realistically achievable within a given time frame. Putting Eq.(8) into Eq.(6) gives us a single equation which defines our possibilities for both a given reduction of fossil fuels and a desired ratio of renewable sources.

$$\begin{gathered} p_T = 0.88p_F + 0.064(r_1\frac{1+p_T}{0.064} - 1) + 0.056p_A \\ \text{or, equivalently} \\ p_T = 0.88p_F + 0.056p_A + r_1(1+p_T) - 0.064 \end{gathered} \tag{9}$$

In this equation, p_T can be estimated based on the time frame (i.e. consumption prognoses). p_F is determined based on how much CO_2 emissions have to be reduced. r_1 is more of a political decision, but a goal may be that it should be as high as we can reasonably make it. p_A is then determined implicitly by the above equation.

[11] $1toe$, or 1 *tonne of oil equivalent* is equal to $41.868 \times 10^9 Joule$

Swedish Case Study One might say that if we divide the energy production/consumption into the aforementioned three categories then, obviously, the contribution from all categories must sum up to the total. And when you are aware of it, then sure, it is obvious. But as we will soon see, this can be "forgotten".

The Swedish government has set ambitious plans for reducing the total energy consumption by 5%. Second, they intend to reduce the usage, by volume, of fossil fuels by 30%. Third, they wished to have 49% of their total energy supply come from renewable sources. As we discussed, Eq.(9) has four variables, we have now been given three, and the fourth is implicitly determined. What was said about the third category is not so clear though, but a general political consensus was that nuclear energy has its problems and therefore should not be increased, but rather decreased. In its most general form, Eq.(9) looks as follows

$$p_T = f_0 p_F + a_0 p_A + r_1(1 + p_T) - r_0 \tag{10}$$

where the fractions are given by

$$\begin{aligned} f_0 &= \frac{F_0}{T_0} = \frac{175TWh}{420TWh} \approx 41.7\% \\ r_0 &= \frac{R_0}{T_0} = \frac{180TWh}{420TWh} \approx 42.9\% \\ a_0 &= \frac{A_0}{T_0} = \frac{65TWh}{420TWh} \approx 15.5\% \end{aligned} \tag{11}$$

We then set $p_T = -0.05$, $p_F = -0.3$ and $r_1 = 0.49$ in accordance with the mentioned plans. Solving Eq.(10) for p_A gives

$$p_A = \frac{p_T + r_0 - r_1(1 + p_T) - f_0 p_F}{a_0} \approx 24.6\% \tag{12}$$

Using Eq.(7) we obtain the increase of renewable sources

$$p_R = r_1 \frac{1 + p_T}{r_0} - 1 \approx 8.6\% \tag{13}$$

This is hardly a reduction of nuclear power. In fact, according to these plans, nuclear power has to increase nearly three times as much as renewable energy. Granted, the alternate category could encompass more than nuclear energy. In any case, the full plan, including its implications looks as follows: *(i)* 5% reduction of total energy consumption, *(ii)* 30% reduction of fossile fuels consumption, *(iii)* 8.6% increase of renewable energy consumption and *(iv)* 24.6% increased consumption from alternate sources. Alternate here being either something not yet revealed, or nuclear power [34].

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