POWER FROM GLACIERS: THE HYDROPOWER POTENTIAL OF GREENLAND'S GLACIAL WATERS

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Preface

Hydropower resources, though limited in quantity, must not be neglected in an exploration of future energy supplies. They are inexhaustible, can be used with high efficiency and good economy, and do not produce pollution or waste problems. The known amount of conventional hydropower resources--estimated by the World Energy Conference--might be significantly expanded by the potential inherent in the waters melting from the ice shield of Greenland.

This paper was prepared by the IIASA Energy Program as part of a more general effort to identify and assess energy sources rich enough to contribute significantly to future global energy demand. It is to·be considered a preliminary technical evaluation of the power that could be produced largely based on technology in use today. Some of the problems of the development of this source as well as possibilities of transporting electricity or other products to prospective consumers are addressed. A few of the basic assumptions adopted for this study may still be arbitrary. Therefore, further investigations in situ are needed to test the validity of the findings and conclusions.

Summary

In the southern parts of Greenland, large quantities of water melting every summer from the ice shield 1000 m above sea level and more, within short distance from the coast, offer favorable conditions for a large-scale hydropower development. General ideas on such a development have been published by several authors. This report tries to go a step further by providing a realistic assessment of available resources, an anlysis of technical problems for the utilization of this resource and its integration into a global energy system, and a preliminary estimate of construction needs and costs.

The estimate of available resources is based on published climatological data for Greenland and other arctic stations, and on a cautious selection of effective solar radiation and albedo values. 210-360 km^3 of water is expected to be available during the summer months at an average altitude of 1000 m, corresponding to an energy generation of 460-800 TWh. Continuous generation all-year-round, however, requires storage reservoirs with a total volume of 100-180 km^3. In the southwest, numerous large lakes will provide sufficient storage volumes. In the east, storage is a problem, and power generation might be restricted to the summer months.

Some 12 to 15 sites have been identified on the maps where power schemes can be developed with a total installed capacity of 60-120 GW. Hence the estimated hydropower resources of Greenland come close to the 1974 total consumption of electric energy in the interconnected grid system of Western Europe which according to the statistics of UCPTE [34] was 724 TWh with a peak load of 118 GW.

Technologies for hydropower development are well established and already in progress towards the order of magnitude needed for Greenland. However, methods of collecting water melting from large ice surfaces have still to be studied and tested. The problem of bulk energy transport over great distances is common to all future global energy supply options, and not specific for the Greenland energy. Carriers envisaged in the report are EHV sea cables and transmission lines on land, hydrogen gas pipelines across sea and land, and tankers for liquid hydrogen or ammonia. Preliminary cost comparisons show each of these carriers to be competitive under specific production and market conditions. The report gives a tentative model for the full development of Greenland's glacier power comprising all these options.

Construction costs of the power schemes are estimated at 275-320 US-dollars per installed kilowatt, but another 220-430 US $/kW have to be invested in transport facilities such as EHV links or H_2 gas pipelines. Liquid H_2 as an energy carrier needs lower investments but involves higher energy losses.

The integration of Greenland's glacier power into a global energy system is analyzed according to the criteria adopted for IIASA's Energy Program. No need of fundamental innovation and no serious constraints have been identified for a full development, scheme by scheme, over a construction period of, say, 40 years starting after an initial testing, planning, and design period, of, say, 10 years. A tentative study program is suggested comprising collection of basic scientific data as well as preparatory technical investigations and tests to ascertain the technical feasibility of the development.

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Power from Glaciers: The Hydropower Potential of
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INTRODUCTION

Precedents

"Greenland is no longer the distant romantic ice region where
daring expeditions fight against snowstorms and the danger
of freezing to death. Now Greenland has become a testing
field of many branches of modern science."

These sentences translated from a book on Greenland today
[1] are typical of the trend to conquer this Arctic island
for human needs. The U.S. air base of Thule was one step: 7000
laborers worked there for 18 months creating a city for some
8000 inhabitants with all facilities--not only for the airfield
but also for a seaport. Then Camp Tuto and Camp Century were
built on the ice cap and hundreds of technicians settled there
for a couple of years to undertake exploratory work. All these
stations are at 77° N, an inhospitable latitude compared to the
"green pastures" along the coast of Southern Greenland where
1000 years ago Norsemen settled and started "to raise cattle
and sheep in large numbers". They did so for about 400 years.
Then climatic conditions deteriorated. In the last century,
observations revealed a reverse process: an increase in temper-
ature has been influencing ice conditions in and around Green-
land; pack ice and ice drift have been reduced and gradually
some of the inland glaciers retreated. The annual mean temper-
atures of the period 1914-1943 are reported to be almost 2 °C
higher than those of the period 1881-1910 [2]. Since 1943,
however, temperatures have been declining again.

The enormous mass of ice covering Greenland, combined with
steep mountain gradients to the sea, makes hydropower a promising
resource, and its development might significantly - although not
decisively - contribute to a future energy supply. This is not
a new idea. Among others, the Institute of Engineering Research
of the Kollbrunner Foundation at Rodio, Switzerland, drew public
attention to this energy resource in two of its publications [3]
introducing the idea of the Swiss hydrogeologist Stauber of de-
veloping "glacier power schemes" in Greenland to an extent of
2000-8000 TWh per year equalling 250-1000 GW. Technical details
of Stauber's idea are protected by patents in several countries
including Austria [4]. Notwithstanding the validity and feasi-
bility of many of Stauber's assumptions and methods, the order of
magnitude envisaged in [3] seems too optimistic. Even a more
modest yield, however, could bring Greenland's hydropower poten-
tial to the level of that of entire Europe excluding the USSR

which according to estimates of the World Energy Conference is some 750 TWh per year (85 GW).

This study aims at estimating in realistic terms the available resources, the appropriate technologies for developing them, the investments and other requirements of such a development, and the integration of Greenland's glacier power into an overall power scenario of the future.

Basic Considerations and Assumptions

The present status of interaction between precipitation, surface runoff, production of icebergs and their discharge into the sea, and any other component of the hydrological cycle in Greenland is assumed to be in a permanent balance. Provided that solar radiation and temperature conditions do not change fundamentally in the next decades, this balance can be taken as the basis for considerations of the utilization of melting waters from the ice cap. The melting process during the summer months seems to be characterized by abundant melting during daytime - which is reported to produce numerous small ice lakes on the surface - and partial refreezing during night-time although both midnight sun and diffuse radiation maintain a certain minimum melting. The ice lakes are reported to disappear overnight [1].

If we think of using the melting forces of solar radiation to the extent possible we have two ways to intercept this natural microcycle:

- We may catch the melting waters from the ice surface during daytime and collect them in reservoirs of sufficient depth to prevent them freezing again. In addition to surface drainage of large areas by systems of collector canals, we must try to take in as many natural water discharge channels, streams, and creeks as possible, and direct them to our storage reservoirs. By this method we will reduce the surface runoff to the sea as well as iceberg production, and divert melting waters to the power systems.

- We may increase the heat absorption of the ice cap by darkening its surface, by dispersing material with low albedo, to increase the production of melted water. In this case the balance is artifically changed in favor of an increased tapping of the vast reserves bound in the ice mass of Greenland.

The following suppositions must be true if these methods are to be fully effective:

- That the melting water is contained in the topmost strata of the snow and firn cover where it can be caught by an interlinked network of collector canals and transported to the storage reservoirs.

- That melting water that disappears from the ice surface through fissures and cracks, and flows in deeper horizons of the ice shield (e.g. in intermediate strata of less density) is recovered at the edge of the ice cap where the ice overburden thins out and subsurface streams reappear at a shallow depth where they can be caught by the water ducts of the collector network. If this proves to be practicable, a smaller collector system confined to the border zones is able to drain a much larger area of the ice cap. Ice tunnels acting as subsurface gutters might intensify this process.

- That darkening of the ice surface is technically and economically feasible and sufficiently permanent. Dispersion of dark sand, basalt dust, or any other material from borrow pits on site by special aircraft will be less of a problem than finding the satisfactory balance between the requirements of economy - which means very thin layers of dispersed material - and of stability - which means a dust cover thick enough to prevent it from being easily washed or blown off. Flyash from the big coal-fired power plants of the UK or the USA could be an appropriate material; its transport to Greenland can be done as return load on the tankers needed for transporting liquid hydrogen from the arctic power centers to the consumer regions.

RESERVES AND RESOURCES

General Conditions

Greenland's main ice cap covers an area of 1,726,000 km^2 [5] and its volume has been estimated at 2,600,000 km^3 with a fresh water equivalent of 2,350,000 km^3. This is an enormous amount compared with the fresh water reserves in all inland lakes and rivers on earth which total only 125,000 km^3. The ice cap is in the shape of a lenticular mass bounded in the east and west by mountain chains, the eastern chain being the higher. The surface of the bedrock descends to sea level north of latitude 67° N but south of this parallel it rises to a plateau of about 1000 m elevation with single peaks penetrating the ice cap and forming the so-called Nunataks.

The coincidence of large water volumes with remarkable elevations above sea level at short distances from the shore line in the fjords in favorable for a large-scale hydropower development. However, water will only be available in those parts of the ice cap where climatic conditions allow for an efficient melting process during the summer period. A sufficiently mild maritime climate prevails in the southern part of the island generally south of about 70° N, and only this area is included in the following estimate of reserves and available resources, based on climatic factors and topographical considerations.

In this study, the term "ice cap" is defined as the homogeneous ice shield which covers the interior of the island with modest slopes and almost without significant disturbance by cracks and fissures. Excluded from the area of utilization are border zones where crevices and joints would jeopardize the water collectors, the numerous ice streams which protrude with great velocity (up to 30 m/day) along subglacial valleys to the coast or a fjord, and isolated ice fields or those with no substantial hinterland.

Climatic Characteristics

Temperature

The climate of South Greenland is predominantly moderate arctic, and maritime influences reach up to the ice cap due to the many fjords cutting deep into the land mass. The east coast is less favored, being exposed to pack ice and ice drift for longer periods. Angmagssalik, the only important harbor on the east coast situated at 66° N, is accessible for special arctic vessels only from June through October [1]. The southern end and the west coast, however, are open to every kind of vessel throughout the year up to Holsteinborg at 68° N.

Monthly records of mean and extreme temperatures of many stations in Greenland have been published in Volume 14 of the World Survey of Climatology [5], and by the Meteorological Office, London [6]. Monthly mean temperatures of seven selected stations scattered along the coast between Angmagssalik in the east and Umanak in the west are shown in Table 1. With one

Table 1. Monthly and annual mean temperatures in South Greenland.
(°C)

Station	Latitude	J	F	M	A	M	J	J	A	S	O	N	D	Year
Angmagssalik	65°37'	-7	-7	-6	-3	2	6	8	7	4	O	-3	-5	O
Torgilsbu	60°30'	-4	-4	-3	1	3	6	8	8	6	3	O	-2	2
Nanortalik	60°08'	-3	-3	-2	1	4	5	7	7	6	3	-1	-2	2
Ivigtut	61°12'	-5	-4	-3	O	5	8	10	9	6	2	-2	-4	2
Godthaab	64°11'	-8	-7	-6	-4	2	6	8	7	4	O	-4	-6	-1
Jakobshavn	69°13'	-13	-14	-13	-8	1	6	8	7	3	-4	-8	-11	-4
Umanak	70°41'	-13	-15	-14	-10	-1	5	8	7	3	-2	-5	-9	-4
Average of seven stations		-8	-8	-7	-3	2	6	8	7	5	O	-3	-5	O

Data from World Survey of Climatology [5].

exception (May in Umanak), there are only temperatures above freezing point during the period May through September, while April and October values are partly above and partly below zero. Differences between the coldest and the warmest monthly mean values range from a minimum of 10 °C at Nanortalik (60° N) to a maximum of 23 °C at Umanak(71° N). However, deviations from the mean values must be expected. Fortunately they go in both directions: there can be frost in midsummer while occasional temperatures above freezing point have been recorded in every month of the year, even in January and February at nearly all stations.

Along the coast, the melting period is from May through September, with a rather stable distribution from year to year. Relatively high temperatures are also recorded from the edge of the ice cap. It can be assumed that temperature characteristics of the border zones of the ice cap, where melting waters are to be collected, are similar to those of the coast.

Precipitation

Precipitation is distributed unevenly over the island. Subarctic and maritime influences in the south cause high humidity with annual precipitation up to 2000 mm--more along some coastal strips--propagating also to the ice cap's border zones, whereas the ice cap itself receives less snow the higher the elevation and the latitude is. The arctic climate of Central and North Greenland is characterized by annual precipitation figures of 200 mm and less. A year's observation records for a few relevant stations drawn from various sources [5,6] are given in Table 2.

Table 2. Monthly and annual mean precipitation in South Greenland (mm).

Station	Latitude	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
Angmagssalik	65°37'	58	82	62	53	54	44	35	62	76	90	86	68	770
Torgilsbu	60°30'	151	224	123	119	235	159	71	96	239	192	166	165	1940
Nanortalik	60°08'	64	71	41	59	45	80	53	92	119	125	94	52	895
Ivigtut	61°12'	92	129	87	79	89	96	82	97	162	172	146	77	1308
Godthaab	64°11'	26	24	18	25	29	46	59	69	84	71	44	20	515
Average south coast		78	106	66	67	90	85	60	84	136	130	107	76	1085
Jakobshavn	69°13'	10	13	14	15	20	19	35	34	41	29	21	18	269
Umanak	70°41'	25	15	12	13	12	12	12	12	21	18	25	24	201
Eismitte	70°54' el.3000m	15	5	8	5	3	2	3	10	8	12	13	25	109

Data for coastal stations from World Survey of Climatology [5], for Eismitte from Tables of Temperature, Humidity and Precipitation of the World [6].

Generally there is not much precipitation in July and August which means that sunshine is prevalent during these months - an important finding for the production of melted water. It also means that the predominant source of water available for hydro-power generation is melting from large areas of the inland ice while direct discharge from rain during the summer months is negligible.

From isohyetal maps in the Climatologic Atlas of Europe [7] the total precipitation on Greenland south of 71° N is estimated at 320 km^3 over an area of 860,000 km^2, corresponding to an average of 370 mm per year.

Solar Radiation

World-wide records on solar radiation have been collected by the University of Wisconsin and published in World Distribution of Solar Radiation [9]. In this register of several hundred observation stations, Greenland is represented with a few single values for Thule; no year-long records for stations in South Greenland are to be found. Stations in Alaska, Canada, and the USSR at latitudes between 60° and 70° N show fairly uniform long-term averages of daily global radiation (direct plus diffuse) and can be applied to Greenland with a high degree of probability. The average of the five stations listed in Table 3 may serve as a basic assumption for the Greenland study, equaling an annual mean of 210 cal/cm^2 · day or an annual total of 77 kcal/cm^2 (see also Figure 1).

Table 3.   Solar radiation records.

Monthly means of the daily totals of solar radiation (direct + diffuse) on a horizontal surface (cal/cm^2 · day)

Station	Latitude	J	F	M	A	M	J	J	A	S	O	N	D	Year
Barrow, US	71°18'	3	40	191	403	501	547	424	254	115	41	7	O	210
Fairbanks, US	64°49'	19	76	233	385	477	527	444	363	184	86	27	6	236
Aklavik, CDN	68°14'	5	50	202	388	515	528	446	297	156	62	11	1	222
Reykjavik, IS	64°08'	12	56	138	264	396	366	406	298	165	66	18	5	182
Arkhangelsk, SU	64°30'	1O	46	172	343	348	462	461	331	141	59	14	5	199
Average of the five stations		1O	55	185	360	450	480	435	310	150	65	15	5	210

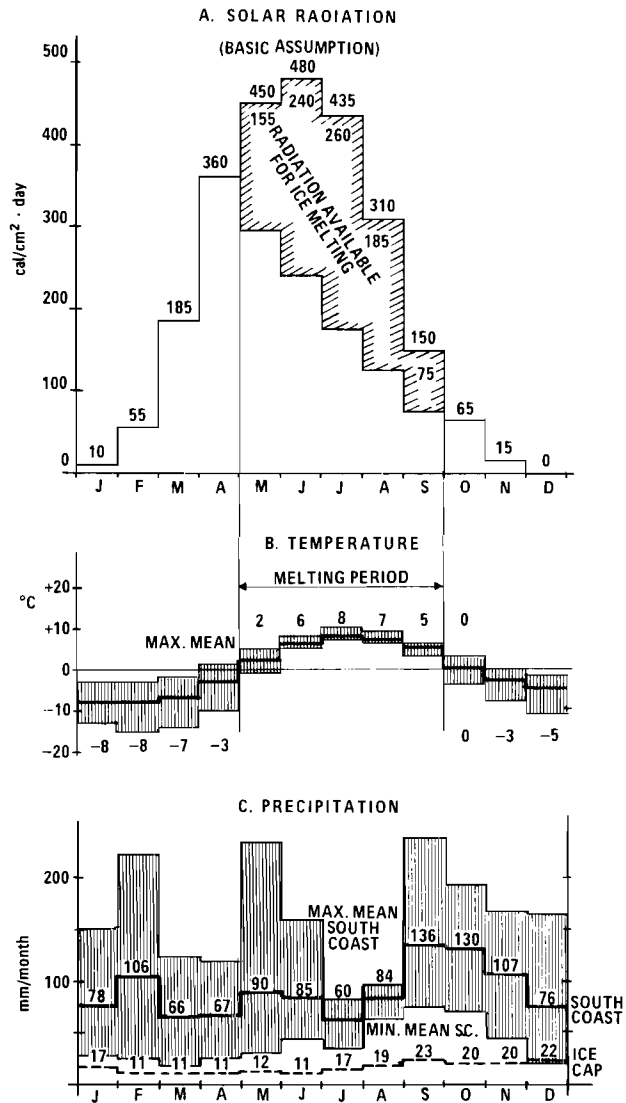From World Distribution of Solar Radiation [9].

Figure 1. Climatic characteristics of South Greenland.

Some remarks on the specific insolation conditions of Greenland are to be found in Volume 14 of the World Survey [5]. Insolation on the ice cap is reported to be rather high due to the relatively high number of sunshine hours and the low water content of the air. Weststation situated on the edge of the ice cap near Alfred Wegener's Peninsula (71°15' N, 51° W, 1000 m el.) is said to receive 170 kcal/cm^2 · a, and Eismitte (70°54' N, 40°42' W, 3000 m el.) had recorded "a little more". This would equal an annual mean of 465 cal/cm^2 · day, about 2.2 times the value given in Table 3. This high value seems to have been derived from normal direct beam records and cannot be applied to the almost horizontal surfaces of the glaciers. Relevant mean values for the summer months would go up to 1300 cal/cm^2 · day which is much more than the highest values of 700-800 cal/cm^2 · day recorded in [9], among others, for some stations in the Antarctic at 2400-2700 m altitude. From these antarctic records one could assume higher than average values for Greenland also. A reasonable alternative is a mean annual insolation of 20% more than the basic value, i.e. 252 cal/cm^2 · day corresponding to an annual insolation total of 92 kcal/cm^2.

Loewe [10] gives indications on the monthly distribution of insolation on Greenland over the year. Applied to the assumption of 92 kcal/cm^2 · a, this distribution allows assessment of alternative solar radiation values for each month according to column 2 of Table 4.

Table 4. Assumptions for solar radiation in Greenland.

Month	1 Global radiation Basic (cal/cm^2 · day)	2 Alt.	3 Radiation available for melting Basic (cal/cm^2 · day)	4 Alt.	5 Solar energy input/month available for melting Basic kcal/m^2	6 Alt. kcal/m^2
Jan.	10	0	–	–	–	–
Feb.	55	30	–	–	–	–
Mar.	185	110	–	–	–	–
Apr.	360	370	–	–	–	–
May	450	630	180	250	56,000	77,000
Jun.	480	700	240	350	72,000	105,000
Jul.	435	600	260	330	80,000	102,000
Aug.	310	350	185	210	57,000	65,000
Sep.	150	150	75	75	22,000	22,000
Oct.	65	60	–	–	–	–
Nov.	15	0	–	–	–	–
Dec.	0	0	–	–	–	–
Year	210	252	.	.	287,000	371,000

Basic assumption: Average of the five arctic stations from Table 3.
Alternative assumption: Basic assumption + 20% with distribution according to Loewe [10].

Even apart from the albedo effects introduced in the next section, not all global radiation will be available for producing water from snow and ice. Firstly, it is expected that melting only occurs in months with average temperatures above zero, i.e. May through September. Gerdel [11] made an estimate of occurrences of melting on the ice cap during the midsummer season June through August, and found that south of 67° N considerable melting may be expected even at elevations as high as 2700 m. The number of midsummer days with temperatures above 0 °C is reported to be reduced from 92 days to 91-92 days at 1000 m, 86-90 days at 1500 m, 66-69 days at 2000 m, and 41 days at 2500 m. Further limitations of efficiency exist:

- A portion, say 10%, of the energy available for melting might be used to heat up the ice from lower temperature levels to 0 °C [12], and another small percentage is needed to keep the water warm enough for transport, storage and operation.

- Not all melted water is available for runoff; some seeps into deeper layers and refreezes [13].

A cautious assessment is that not more than 50% of the net radiation during May through September will be effective for melting. With some arbitrary variation of the reduction factors between 40 and 60% in single months, the effective input of solar radiation is estimated as shown in columns 3 and 4 of Table 4. Columns 5 and 6 show the conversion to the technical units used for further data processing. Radiation input available for the melting process during the summer season ranges from 290,000 to 370,000 kcal/m^2.

Heat Absorption and Available Melting Water Volumes

The albedo of the ice cap of Greenland is estimated to be more than 80% globally. In the coastal area, however, there are places where during summer months the albedo is even less than 20%. This is especially pronounced in July and August [5].

Sellers [14] registered specific albedo values for various surface conditions. For this study records have been selected, and the absorption of solar radiation has been used as shown in Table 5:

Table 5.

Surface	Albedo	Absorption
Fresh snow	75 ··· 85 ··· 95%	15%
Old snow	40 ··· 60 ··· 70%	40%
Ice	30 ··· 40%	60%
Darkened surface	5 ··· 10 ··· 15%	90%

Further considerations are based on two models:

Model 1 without artificial darkening, assumes that one-third of the ice cap area is covered by fresh snow, old snow, and ice. This is not only an integral over space but also over time. The average absorption of this model is

$$\frac{1}{3} (0.15 + 0.40 + 0.60) = 0.38$$

and efficient heat absorption amounts to

$$0.38 \ (290,000-370,000) = 110,000-140,000 \ kcal/m^2$$

for the whole summer.

Since melting of 1 m^3 water from ice requires 80,000 kcal, the heat absorbed would result in a melted depth of 1.40-1.75 m of water. This result fits very well into a statement of Loewe [10] that 1.5 m of ice is melted during a year at 71° N and 1000 m elevation.

Model 2 considers the possibility of artificial darkening of the snow and ice surface. Given the extensive areas consider-ed for utilization it will never be feasible to cover them with a complete layer of low-albedo material [15]. A cautious assump-tion is that one-quarter of the total area can be treated this way. The remaining three-quarters is again equally distributed among fresh snow, old snow, and ice. Average absorption of this model is

$$\frac{1}{4} (0.90 + 0.15 + 0.40 + 0.60) = 0.51$$

and efficient heat absorption

$$0.51 \ (290,000-370,000) = 150,000-190,000 \ kcal/m^2 \ for$$

the whole summer

sufficient to melt a depth of 1.90-2.40 m of water. Thus darken-ing of one-quarter of the entire area results in an extra melt-ing of 0.50-0.65 m of water.

Geographical Criteria

Topographic conditions of Greenland south of 72° N have been studied in a preliminary manner by using the USAF Operational Navigation Chart issued by the US Aerospace Center, St. Louis, Missouri, ONC sheets C-13 and D-16. These are maps 1:1,000,000 with 1000 ft (~ 300 m) contour lines and sufficient terrain characteristics to give overall information on sites suitable for a glacier power development. Figure 2 is a sketch 1:5,000,000 of South Greenland copied from the Times Atlas of the World of 1973 [8], and amended by the border line and contour lines of the ice cap as well as other details from the ONC sheets.

For climatic reasons, considerable melting waters are to be expected only south of about 71° N, and the study is confined to this area of the island. On the east coast, topographic conditions give a further constraint. South of the Scoresby Sound (70° N) down to the Watkins Fjord (68° N, 32° W) the edge of the ice cap is mostly at elevations high above the ablation zone, and always too far from sea level for any reasonable development.

Around the Gardiner Lake (68°30' N, 33° W, 850 m el.) a glacier power scheme seems feasible although conditions do not allow a large-scale development there. More favorable conditions are to be found south of Angmagssalik (66° N) where the ice cap is a suitable distance from some fjords and has considerable extent. The coastal mountain chain goes up to altitudes of 1000-1300 m. A disadvantage is the lack of natural lakes or other opportunities for storage on rocky ground. Storage reservoirs must be provided on the ice cap itself. In some parts of the southeast, the ice cap protrudes right out to the coast with almost no mountainous border zone between ice and ocean.

More favorable conditions might be found at the southern end of Greenland, if also in minor catchment areas of about 5000 km^2 only. Near Narssarssuaq (61°31' N, 45-46° W) several natural lakes at elevations of 800-1000 m offer storage facilities at a distance of not more than 10 km from the coast of the Bredefjord and its branches.

Suitable conditions continue along the west coast until about 67° N at Söndre (Southern) Strömfjord. Steep fjords cut into the land mass and every now and then approach the edge of the ice cap which is generally at an altitude of 800-1000 m. Mountain valleys between the fjords contain a considerable number of smaller and bigger lakes at various elevations. They favor hydropower development in a chain of plants with very short aqueducts making use of the heads between the lakes and finally to the sea.

A specific phenomenon exists north of the Strömfjord between parallels 66° and 68° N: the ONC sheet C-13 shows a
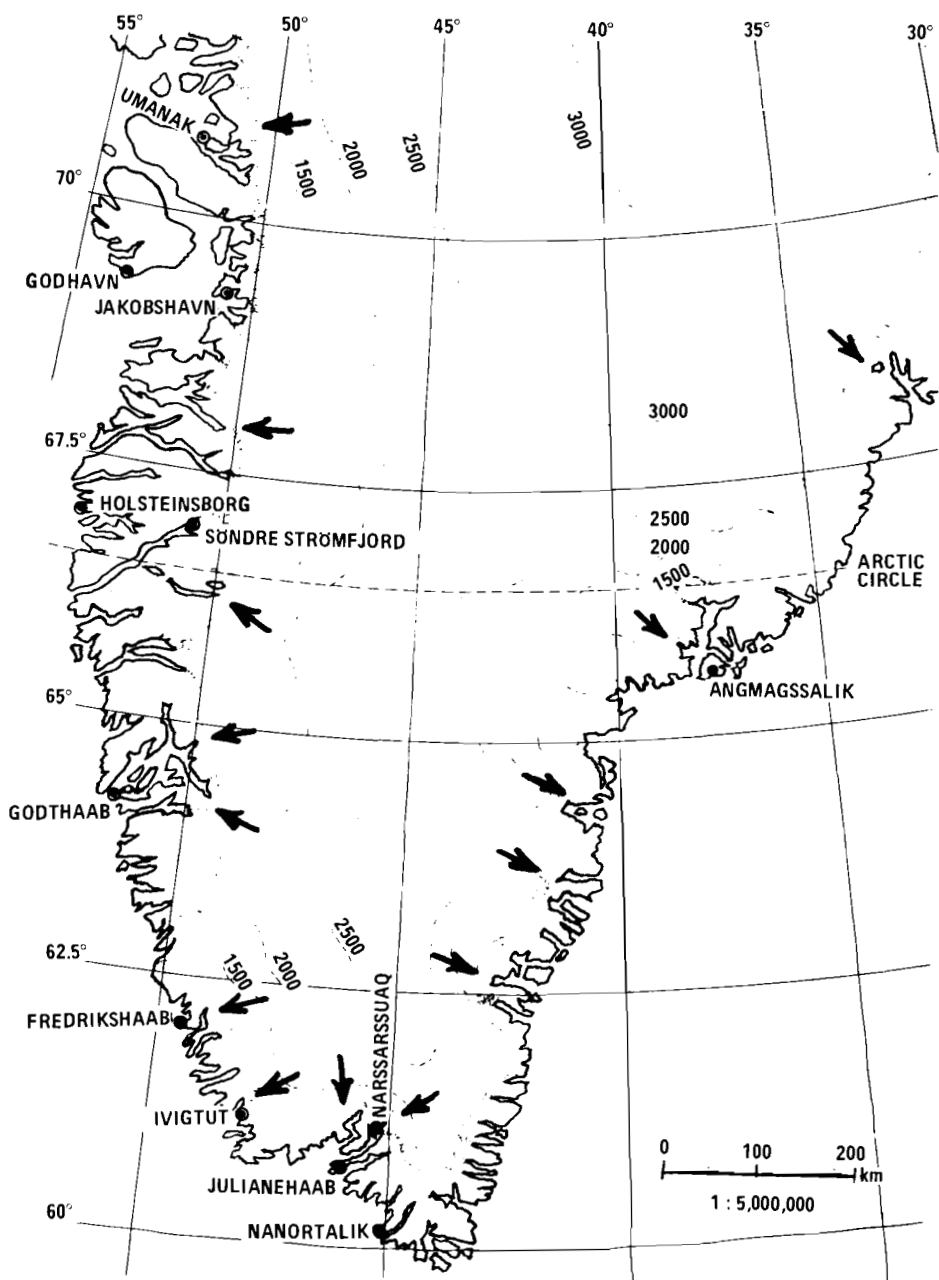
Figure 2. South Greenland.

large number of ice lakes scattered over the surface of the ice
cap at altitudes of 600 to 1800 m, with obviously permanent sur-
face water ducts between each other (66° N) or as isolated lakes
without surface discharge (68° N). This phenomenon will certain-
ly favor water collection and storage but is partly counteracted
by the disadvantage of a gross head of only some 500 m being
available between the edge of the ice and the coast.

North of 68° N the ice cap comes close to the shore of the
Disko Bay and the Umanak Fjord (71° N) with but a narrow and
low mountain zone fragmented by tremendous ice streams. The
Jakobshavn ice stream is reported to be one of the biggest
producers of icebergs. Here hydropower development will find
a natural limit, or at least it will be hampered by the frag-
mentation of the catchment areas.

Estimation of Glacier Power Reserves

Hydroenergy can be made available from those areas of the
ice cap where ablation during the summer period is sufficient
to produce considerable amounts of water. A schematic cross
section through Greenland along the 65° N parallel is shown in
Figure 3, with glaciation details taken from a report on the
International Glaciological Expedition 1957-60 to Greenland
[16]. The zone of ablation extends from the edge of the ice
cap up to elevations of 2200-2300 m (7500 ft) and is larger
and less inclined along the western slope than in the east.

Benson [17] distinguishes four different glacier zones:

- the dry snow zone with no melting at all;

- the seeping zone with some melting water seeping into
  the firn and refreezing there;

- the soaking zone where the firn is filled up with
  melting water and produces runoff; and

- the ablation zone where the snow cover is completely
  melted off during summer.

From Golubev's theory [13] it becomes evident that only the third
and fourth zones have water runoff during the summer months and
can be regarded as a glacier power resource. Benson estimates
the width of the third zone in Southwest Greenland at about
50 km, and that of the fourth about 100 km--in very good agree-
ment with the Häfeli sketch reproduced in Figure 3.

From the ONC sheets the entire area between the edge of the
ice cap and the 7500 ft (2200-2300 m) contour line, from 69° N
in the east to 72° N in the west is assessed at roughly 250,000
km^2. Under Model 2 conditions (see earlier) the area provides a
water yield of 250,000 km^2 × (1.90-2.40 m) = 475-600 km^3 per
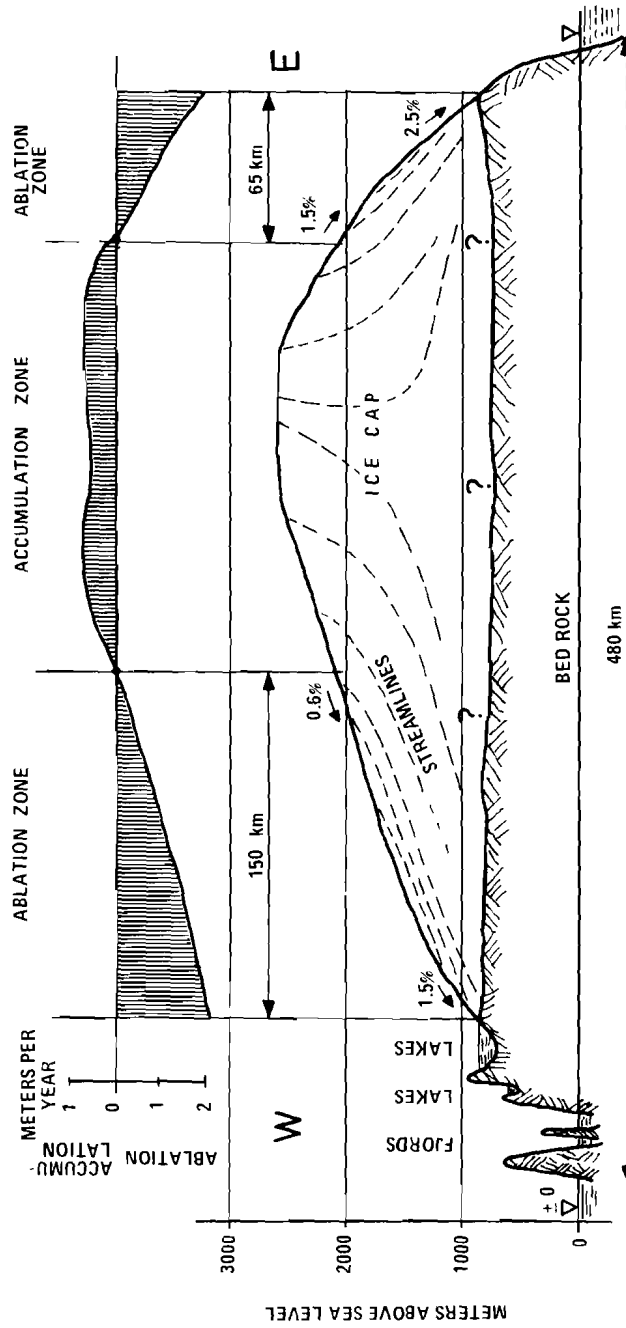year and over an average gross head of 1000 m corresponding to

Figure 3. Cross section through Greenland along 65° N latitude.

an energy equivalent of 2.2 TWh/km^3 of water, this volume is able to generate (475-600 km^3) × 2.2 TWh/km^3 = 1050-1320 TWh equal to a continuous power flow of 120-150 GW. These amounts represent the technically feasible reserves of Greenland's glacier power.

Available Glacier Power Resources

In a preliminary survey of the ONC sheets, 12-15 sites could be identified where large-scale hydropower schemes might be developed. Some features of these sites are:

Catchment area	3,500-22,000 km^2	average 10,500 km^2;
Intake elevation	300-1700 m	average 1000 m;
Distance from intake to shore	5-22 km	average 11 km;
Available reservoir area outside ice	0-250 km^2	average 60 km^2.

The schemes cover a total area of about 150,000 km^2. Available resources from this total area according to Models 1 and 2 (see earlier) are estimated in Table 6.

Table 6.

	Model 1	Model 2
Total area deployable	150,000 km^2	150,000 km^2
Melting water depth	1.40-1.75 m	1.90-2.40 m
Total water from area	210-260 km^3	285-360 km^3
Average gross head	1000 m	1000 m
Hydro energy equivalent	2.2 TWh/km^3	2.2 TWh/km^3
Energy potential	460-575 TWh	625-800 TWh
Continuous power flow	52-65 GW	70-90 GW
Installed capacity at 8000 h/a	58-72 GW	78-100 GW
6000 h/a	77-96 GW	104-133 GW
4500 h/a	102-128 GW	140-178 GW

Critical Remarks

The estimate of available resources gives annual water yields of 210-360 km^3. This is approximately in line with the annual precipitation on South Greenland's total surface which is 320 km^3 (see earlier). A portion of the precipitation will continue to flow to the sea in surface rivers or ice streams without going through the turbines. Development of glacier power resources, especially under the conditions of Model 2, will cause additional tapping of the ice deposits of the order of perhaps 100-200 km^2 a year. This is a negligible amount compared with the total ice volume of 2,600,000 km^3.

It is not yet evident whether a permanent system of drainage of large ice areas is technically or economically feasible. There may be doubt whether an assumption of 150,000 km^2 as a deployable catchment area is realistic. However, there are reserves not included in the assessment of the water yield: only 50% of the radiation input has been introduced as being effective, only one-quarter of the area has been adopted in Model 2 for surface darkening, and current precipitation has been neglected. The smaller the area involved, the more intense the utilization will be and the more it will concentrate near the edge of the ice cap where precipitation and insolation are highest and technical obstructions to an efficient development lowest. The assumptions of this study, therefore, appear to be valid and reliable over a wide range of conditions, and have by way of compensation a rather low sensitivity to changes of any one of the parameters.

TECHNOLOGY

Introduction

Established, as well as new, technologies will be needed for a large-scale development of Greenland's glacier power resources. Collection of melting waters from large ice areas has not yet been attempted, and optimal methods must be explored. Storage of water will hardly cause problems of technology as long as reservoirs of sufficient size can be embedded in the mountain chains bordering the ice cap; shaping reservoirs in the ice cap itself, however, calls for new ideas. The subsequent transformation of the potential energy of water into kinetic and finally electric energy can rely on well-advanced techniques. Energy transportation from remote generation sites in the arctic to consumption centers in Europe and North America or elsewhere is a problem also with other global power parks envisaged as future energy supply options, and needs no special innovation for Greenland.

The hydropower potential of Europe has been developed since about 1890 and will continue to be, approaching its limit of 750 TWh per year perhaps by the year 2000. During this century

of evolution the size of individual stations has gradually
shifted from the megawatt to the gigawatt level. The Greenland
option has to start at the gigawatt or even multiple gigawatt
level from the very beginning. However, the unit size of
hydropower stations cannot be increased arbitrarily since it
depends on conditions offered by nature. Stauber's assumption
of a unit size of about 25 GW with a catchment area of 40,000 km^2
sounds unrealistic. Although the ice cap extends over a practi-
cally infinite area, its border zones - where water intake has
to be established - are divided by glacier streams, mountain
valleys and fjords which give no scope for unlimited development.
The tentative schemes identified on the ONC maps cover an aver-
age catchment area of 10,000 km^2. This is about 10 to 50 times
the catchment area of conventional high-head schemes in Austria,
Switzerland or Norway. In the east and southwest of Greenland
even larger concentrations seem feasible although the lack of
adequate storage opportunities might produce adverse results.
Along the west coast, an optimal correlation of ice areas and
natural lakes available for storage might split up such a
10,000 km^2 unit into several subunits with independent power
stations, linked by EHV transmission lines to a central electrol-
ysis plant for conversion into a transportable form of energy.

Essential data for a "5 GW-standard glacier power scheme"
have been collected in Table 7. They give the basis for detailed
considerations in the following sections on dimensioning the
necessary construction components.

Table 7. Basic data of the "5 GW standard glacier power scheme".

Unit catchment area	10,000 km^2
Range of melting water depth (see text)	1.40-2.40 m
Water volume available from unit catchment area	14-24 km^3
Required storage volume (see text and Figure 4):	
at 8000 h annual operation	8.1-13.9 km^3
at 6000 h annual operation	6.3-10.8 km^3
at 4500 h annual operation	3.9-6.7 km^3
Turbine flow at 8000 h/a	485-835 m^3/s
at 6000 h/a	650-1110 m^3/s
at 4500 h/a	865-1480 m^3/s
Energy equivalent for average gross head 1000 m	2.2 TWh/km^3
Energy available per year and scheme	31-53 TWh
Installed capacity for 8000 h/a	3.9-6.6 GW
for 6000 h/a	5.2-8.8 GW
for 4500 h/a	6.9-11.8 GW

Total hydropower potential of Greenland allows for 15 schemes of the standard
size, i.e. 460-800 TWh equivalent to a power flow of 52-90 GW. Total installed
capacity might amount to 60-120 GW.

Water Collection

For the time being we do not dispose of the proved method for collecting water from the surface of large areas. A system of surface canals acting like gutters and as an aqueduct will be the basic requisite. The canals should have parabolic or triangular shape and a minimum depth of a few meters in order to warrant concentration of variable flow in a narrow profile and, together with a gradient not less than 0.5%, sufficient water velocity and turbulence to avoid refreezing of the water. Bulldozers and snowmills might be used to construct the canals in an easy and cheap way. Such equipment has successfully been applied in constructing the ice-shelters of Camp Tuto and Camp Century in the Thule district [1]. The Kollbrunner Institute offers other suggestions in its publication no. 27 [18] dealing with ice engineering methods and equipment. Heat-absorbing PVC lining, forced melting by flues heated from motor-exhaust, by electric resistance heating from mobile generators, or by use of the heat of nuclear waste containers could support the excavation.

The canals must form a criss-cross network so that every drop of water has several chances to reach the reservoir. Otherwise a local discontinuity in one canal - caused by ice movements, snowdrift or other hazardous impacts to which the canals are highly exposed - could make the entire system inactive. Ice tunnels of larger section could perhaps expand the canals in lower portions near the edge of the ice cap, and at the same time help to drain subsurface water into the storage reservoir.

It has to be tested whether a few main collectors as suggested by Stauber and patented by him [4] will be sufficient to drain the entire area under consideration. They have to be augmented by the use of natural channels, and by a system of secondary collector trenches like the systems for land irrigation or drainage. Irrigation systems for an area of 1 million hectares (10,000 km^2) are not unusual in densely populated zones like India where manpower is easily available and cheap. This is certainly not true in Greenland, but excavation of trenches in ice might be more easily amenable to mechanization and less laborious than in solid soil.

As a very preliminary and tentative estimate, a canal system of 1250 km length is supposed to suffice for an area of 10,000 km^2. During the time of highest solar radiation on a warm July noon, a maximum of 1 m^3/s discharges from every square kilometer of catchment area while the average discharge on this warm day amounts to 0.45 $m^3/s \cdot km^2$, and the mean discharge during the entire melting period of 150 days is about 0.18 m^3/s. (For comparison: the peak discharge from 10,000 km^2 is equal to the 100 years-frequency flow of the Danube in Vienna experienced in the floods of September 1899 and July 1954. This may suffice to illustrate the order of magnitude inherent in the development of Greenland's glacier power resources.)

The total ice excavation for a 10,000 km^2 collector system feeding a 5 GW standard power scheme is estimated at 50-80 × 10^6 m^3. In conventional hydropower, earth movements up to 50 × 10^6 m^3/GW are quite common.

Water Storage

Storage in Natural Lakes

Along the west coast, the mountain chains bordering the ice cap carry a large number of natural lakes at various levels up to 1000 m and more. These lakes are to be expected to give an opportunity of large storage reservoirs with only minor dam structures. Similar conditions exist in Norway and Canada. The Churchill Falls scheme in Labrador with an installed capacity of 5 GW disposes of a live storage volume of 31 km^3 which had been created by dams with a total fill volume of 19 × 10^6 m^3 and a maximum height of 30 m.

The storage volume required for balancing the water yields collected with variable discharge during the short summer period against the continuous operation period of the power station depends on the operation characteristics adopted for power generation. Maximum exploitation of the power facilities and minimum investments are achieved with a year-round operation of, say, 8000 h at full load. According to the top graph in Figure 4, this operation requires a live storage of 58% of the annual water yield or in absolute terms 8-14 km^3 for each standard scheme.

In the west, lake surfaces of 150-250 km^2 are available for each standard scheme. The storage volume mentioned above can be achieved with water level fluctuations of 50-100 m. One-third to one-half of this variation might be effected by damming the natural lake level, the rest by lake tapping. The dams will have modest heights between 20 and 50 m. Fill volumes can be estimated from comparable examples in Canada and Norway. The mean reference ratio of these examples is 0.6 × 10^6 m^3 dam fill for each cubic kilometer of live storage. Hence the 5 GW standard scheme in West Greenland may require the very modest amount of 5-10 × 10^6 m^3 of dam fill.

Reduced Storage Requirements

Natural reservoirs of equivalent size are not to be found in the south, where lake surfaces of only 30-40 km^2 per standard scheme are available, let alone along the east coast, where mountain valleys offering a natural storage facility hardly exist. In order to avoid expensively high dams, operation patterns must be adjusted to the availability of smaller storage volumes, and reservoirs embedded in ice must be considered.
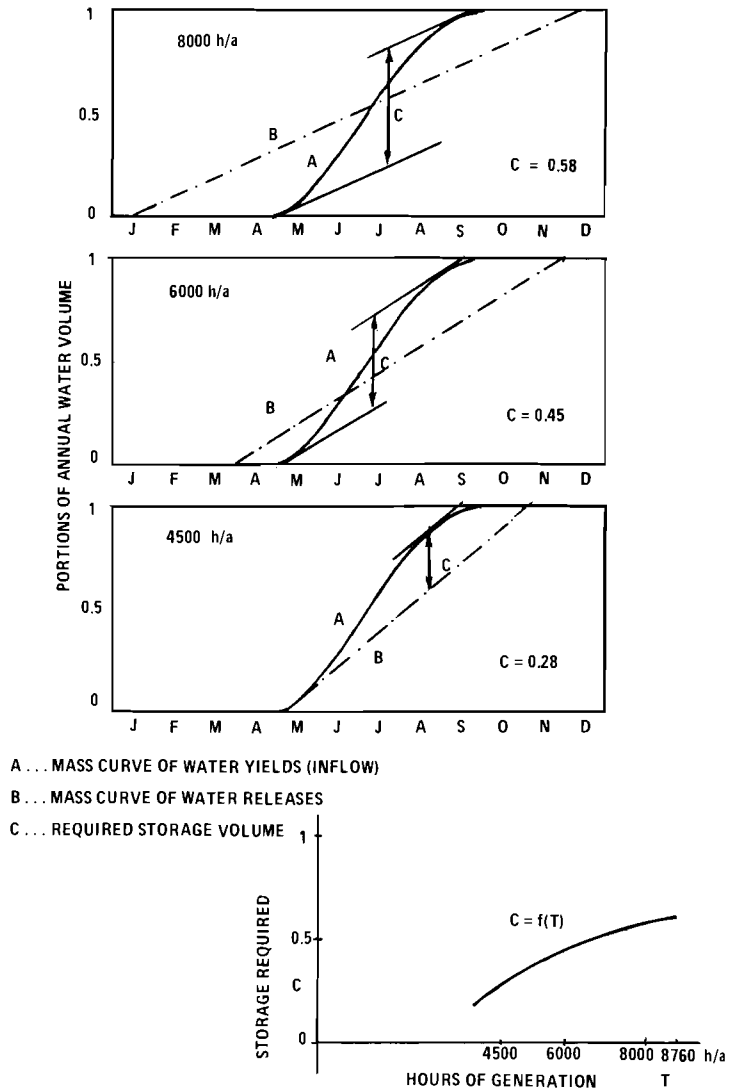
Figure 4. Storage requirements.

Figure 4 includes two assumptions for intermittent power generation, one with 6000 h of full load a year, another with 4500 h, i.e. full load periods of 8 or 6 months a year. Relevant storage requirements decrease to 45% and 28% respectively or in absolute terms to 6-11 km^3 per standard scheme operated 6000 h, and to 4-7 km^3 per scheme operated 4500 h. The operation period of 4500 h (= 6 months) fits in with the access conditions of the east coast where owing to pack ice the port of Angmagssalik can be serviced only during May through September [1]. Lack of natural storage facilities and restrictions on energy transportation in the cases of liquid hydrogen or ammonia on tankers have the same impacts on energy generation.

Reservoirs in Ice

No experience exists on the construction and behavior of ice dams or reservoirs embedded in ice. The technical feasibility of ice as a dam fill material has still to be investigated, and its stability and watertightness to be tested. Provided that the results are satisfactory, the proper method to handle large ice masses poses the next problem. Bulldozers or draglines might be adequate tools to fill an ice dam from parallel borrow trenches. Mobile stripping equipment similar to that used in Germany for open lignite mining, or in Canada for the extraction of tar sands, would combine excavation of large ice cavities with dam filling over its conveyor belt system. A still more efficient method to shape large hollows out of the ice body could be nuclear blasting, provided that contamination is no hazard. Blasting with conventional explosives proved unsuccessful at the air base camps of the Thule district.

The water intake to the power tunnel from the reservoir gives a not less severe problem. Ice does not satisfy the requirements of a safe and stable foundation for intake structures containing gates or valves for controlled water releases, nor for an aqueduct under the pressure of the reservoir level. Hence the reservoir on ice must lean against an abutment or a flank of solid rock of a bordering mountain chain, or against a Nunatak not too far away from that mountain chain. The investigation and selection of adequate sites needs detailed topographical information.

Given the many unknown parameters for constructing reservoirs on ice, a reasonable estimate of amounts of material or other construction requirements is beyond our present knowledge.

Tunnels and Power Stations

Irrespective of the origin of water, its transport through pressure tunnels and penstocks to the turbines of a conventional power station can rely on well-advanced techniques. Their application in Greenland will hardly cause unusual problems. The

Kollbrunner publications [3] mention the phenomenon of permafrost and allot certain advantages to it in tunneling in Greenland. These considerations seem refutable for two reasons. Firstly, permafrost will hardly exist in the mountain chains exposed to maritime weather influences and temperatures above freezing point during many months every year. Further, even if tunnels or penstocks should be driven through permafrost zones, the constant flow of water with temperatures above 0 °C would soon make permafrost disappear in the rock surrounding the water duct.

Tunnels from the final reservoir (the head pond of the power scheme) to the penstock may find favorable conditions in the granitic rock formations of Greenland, similar to those in Norway and Sweden. According to Table 8, the tunnel of a standard scheme operating 8000 h a year has to carry 485-835 m^3/s. This requires a cross section of 120-200 m^2, which is equal to, or even less than, the area of several existing tunnels in Sweden and the USA. For a 4500 h/per year installation, two parallel tunnels might be cheaper than one super-tunnel. If a reservoir comes close to the shore, the Swedish hydropower type with vertical or steep penstocks directly from the reservoir to a power cavern and a long, pressureless tailrace tunnel to the sea might have technical and economic advantages. Tunnel construction for each standard scheme requires gross average amounts of 1.5×10^6 m^3 rock excavation and 250,000 m^3 concrete lining.

Table 8. Energy transport routes Greenland - Europe/North America. (For lengths of sections see Figures 5 and 6.)

Route Ia: Angmagssalik - Iceland - Scandinavia - Central Europe

Route Ib: Narssarssuaq - Iceland - Scotland - Western Europe

Route IIa: Fredrikshaab - Baffin Island - Canada - New York

Route IIb: Umanak - Baffin Island - Canada - Great Lakes

	Routes to Europe		Routes to North America	
	Ia	Ib	IIa	IIb
AC overhead line	2 × 900 km	2 × 1450 km	2 × 1900 km	2 × 2600 km
DC over head line	2 × 700 km	2 × 800 km	2 × 800 km	2 × 1600 km
Sea cable	1950 km	2050 km	800 km	800 km
Route length	3550 km	4300 km	3500 km	5000 km
Circuit length	5150 km	6550 km	6200 km	9200 km

The penstocks have to feed the turbines under an average head of 1000 m with a total flow of 485-835 m^3/s equal to the tunnel flow. In the Churchill Falls plant in Canada the rated

discharge is 2000 m^3/s distributed to 11 penstocks for 186 m^3/s
each under a head of 320 m. In the Malta project of Austria
an inclined pressure shaft for 80 m^3/s under a head of 1000 m
had been designed, and only less favorable geological conditions
caused a review of the design and the change to a manifold pen-
stock on the surface. Dimensions required for the Greenland
glacier power scheme combine essential features of both exist-
ing schemes and should be technically feasible, the more so in
view of the designer's freedom to distribute the total flow to
an adequate number of parallel penstocks of limited capacity.
Average requirements for the penstocks of the standard scheme
can be estimated at about 200,000 m^3 of rock excavation (probably
done by tunnel moles), 50-80,000 m^3 of concrete and 40-70,000 t
of steel lining.

The standard power station in the basic case of 8000 h per
year operation has an installed capacity of 4-6 GW, a size
already existing in Canada and the USSR. Even the jump to 12 GW
in case of 4500 h operation is feasible with regard to the over-
all outlay. Still open is the type of turbine to be applied.
The largest hydropower units of today are of Francis type work-
ing under low and medium heads. Extreme prototypes of Francis
turbines are those of the Grand Coulee extension in the USA with
unit capacities of 600 and 700 MW under a head of 100 m, and
Hornberg in the FRG with 250 MW under a head of 630 m. In
Norway quite a number of big Francis turbines have been installed
with unit capacities between 100 and 160 MW under heads of
400-500 m. Heads of 1000 m or more are now being utilized by
Pelton turbines. Their unit capacity does not exceed 70 MW with
a rated flow of only 10 m^3/s. For the Greenland glacial power
development, either a modified turbine type with both high head
and high flow has to be developed, or a one-step development has
to be avoided. The lakes along the west coast offer good oppor-
tunities to divide the power scheme into two or more subsequent
steps with not more than 500 m individual head. This allows
the stations to be equipped with conventional Francis turbines
within the range of present technology.

The generator type has to be selected in view of the power
application or conversion. AC is the dominating system of
electricity supply and powerful generators of this system have
been installed all over the world. For Greenland power schemes
closely linked to a large electrolysis plant producing hydrogen
or ammonia, DC generation might have advantages. In this pre-
liminary study, the final decision cannot be anticipated, but
will have no significant influence on technical or investment
considerations. Construction and equipment requirements of the
5 GW standard power station may amount to 100,000 m^3 of concrete
and 100-150,000 t of steel including machinery.

Power Application and Transfer

Only a small portion of the energy from the glaciers will
be used in Greenland for domestic and industrial purposes. The

abundant power supply may stimulate processing of natural resources known in Greenland such as iron ore, various non-ferrous metals, uranium and thorium [1]. Demand for processing local resources, however, may not exceed 5% of the energy produced in the glacier power schemes. The bulk of energy will be available for the supply of consumer centers in Europe and North America.

Options for energy transportation from Greenland to prospective consumer regions, or for large-scale application in Greenland are indicated in the following paragraphs.

Conventional Transmission Systems

Figures 5 and 6 give a preliminary selection of routes for connecting energy production centers in Greenland with consumer centers in Europe and Northern America. In tracing the routes, attention has been paid to minimizing ocean crossings and making best use of islands and natural rises of the ocean bed, in order to find practicable water depths and as many intermission points as possible. These points subdivide the long transmission lines into pieces of not more than 600 km in order to secure their stability by adequate technical measures and installations.

Transmission to Western Europe is handicapped by a considerably larger portion of open sea: the total distance of some 4000 km is almost equally distributed between sea and land. Energy supplies to North America are favored not only by much shorter distances across the ocean west of Greenland but also by the fact that the transmission lines on land pass through wide areas of barren land where the right of way can be obtained much more easily than on European territory. Distances to New York and Chicago are 3500 and 5000 km respectively. The large hydro-power schemes on the Churchill, Manicouagan, Saguenay, and St. Lawrence rivers are valuable points of support to the transmission line stability.

The selection of the most suitable transmission system depends on more in-depth studies anticipating future trends. Comments on conventional systems are:

- AC transmission lines are to be preferred for connecting single power stations to a central feed point into the transmission link over the sea, and for the final portions of the line where junction to national and regional networks must be possible. The long-distance link could be a 1100 kV line with bundled conductors with a capacity of 5 GW per circuit. For sea cables, however, AC is less suitable given the present status of technology. The Swiss publications on Greenland's glacier power [3] suggest a 1140 kV three-phase transocean link consisting of three conductor cables with longitudinal and shunt compensation by synchronous motors.
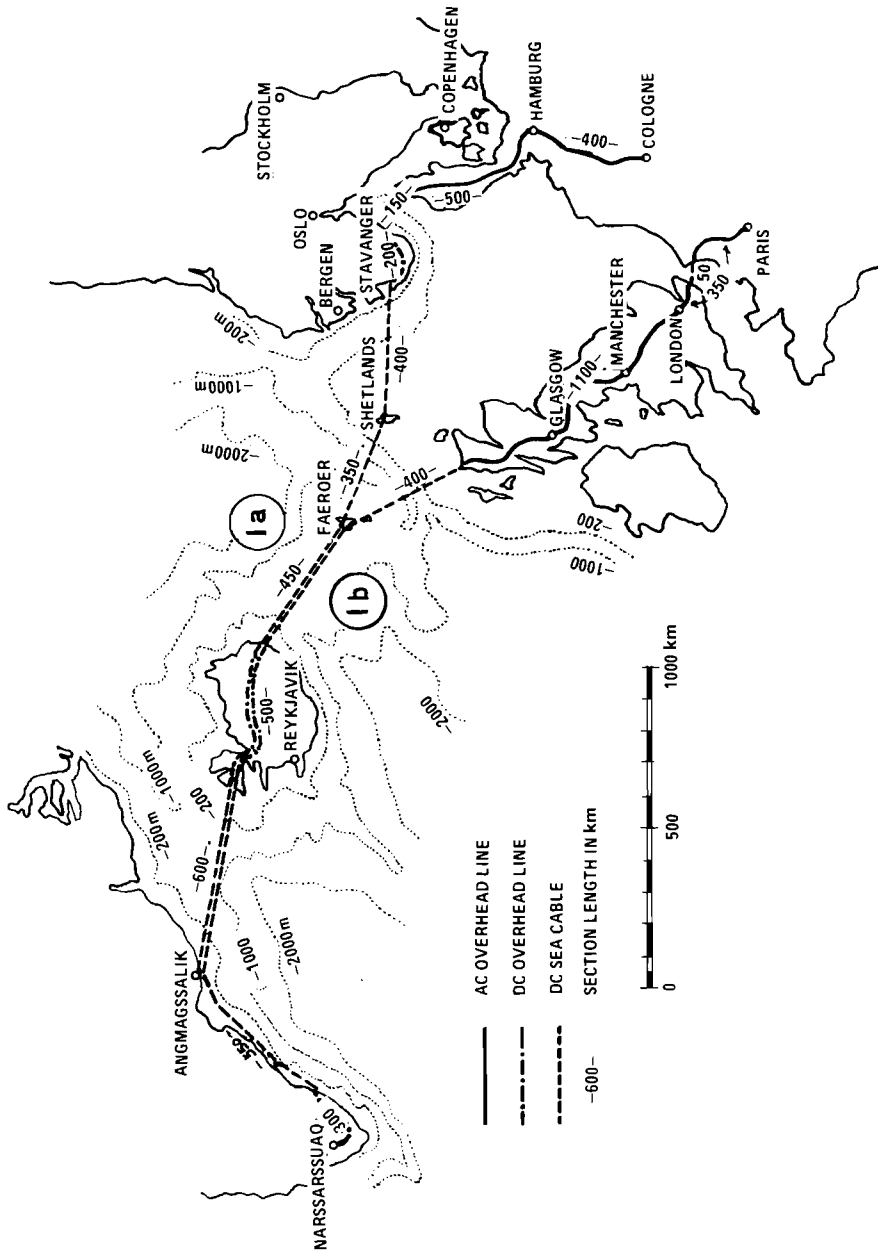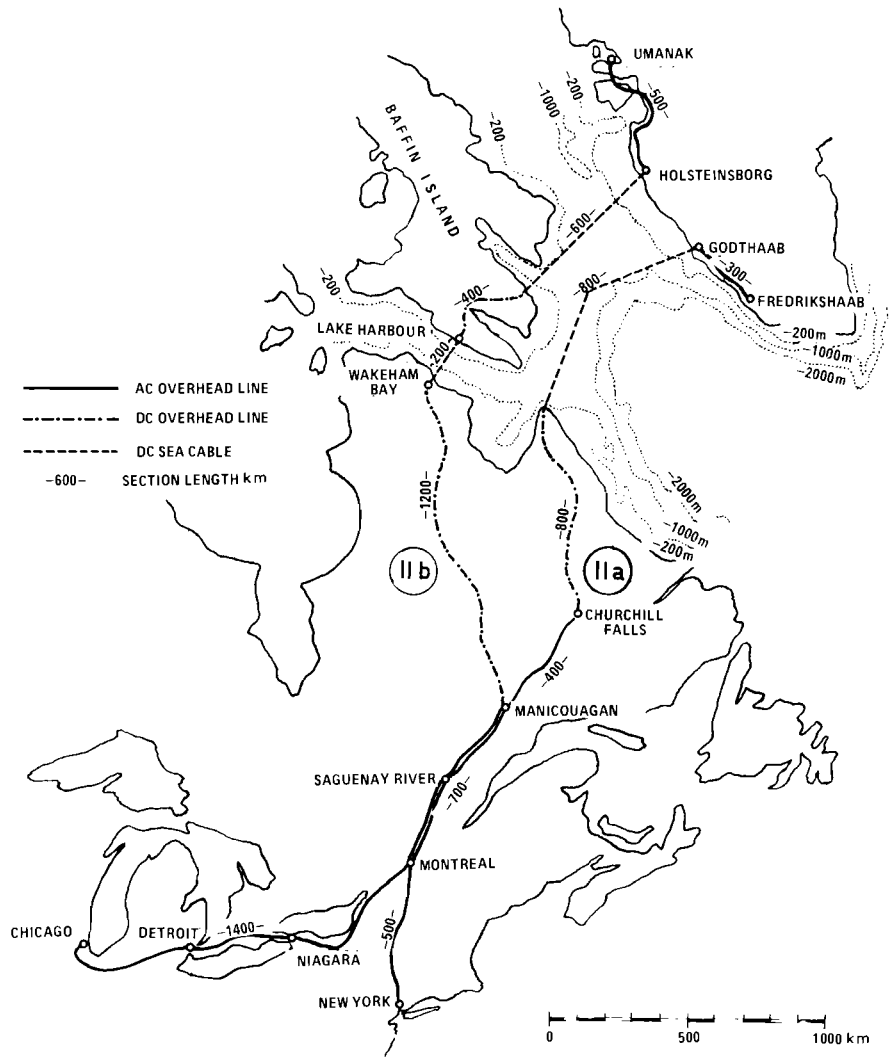
Figure 5. Transport routes, Europe.

Figure 6. Transport routes, North America.

- DC is the best system for sea cables. Existing prototypes operate under voltages up to 500 kV. A transport capacity of 10-15 GW would be warranted by 750 kV oil cables or by 400 kV super-conductive cables [19]. Both are actually studied in EHV laboratories while 1000 kV cables are still regarded as utopian. On land, +500-+750 kV DC overhead lines have already been built, e.g. for the +500 kV transmission line of 1700 km between the Inga power scheme and the Shaba mine district in Zaire [20]. This line consists of two circuits with bundled conductors of three 750 mm^2 steel-reinforced aluminum wires each, supported by some 8500 towers. If 750 kV sea cables become feasible, a transport link combining them with +750 kV DC-overhead lines might be the most convenient connection between the initial AC-DC converters in Greenland and the DC-AC converters in Denmark, Scotland, and Canada where supply into the consumer networks will start. DC lines need less conductors per circuit than AC lines (two against three for overhead lines, one against three for sea cables with the sea as return duct) and have lower transport losses in conductors of equal cross section. These advantages might make up for the additional converter expenses.

EHV cables are inclined to have more faults and outages than overhead lines. In order to bring the transport safety of the cable link to the safety level of the double-circuit overhead line, a spare cable for each route has to be installed in addition to the active ones. Along the selected routes, the sea is generally less than 600 m deep, where cables can be laid on the bottom. If channels of greater depth have to be crossed, technology has still to be found for cable-laying, or suspended cables have to be developed. They have to float at such a depth below sea level that wave action or icebergs cannot destroy them.

For transporting approximately 10 GW over each of the four routes described in Table 8, requirements for overhead lines with bundles of two conductors, and sea cables of relevant capacity and safety are summarized in Table 9.

Table 9.

Route	Ia	Ib	IIa	IIb
AC double circuit overhead				
route length (km)	900	1450	1900	2600
wire = route ×6×2 (km)	10800	17400	22800	31200
DC double circuit overhead				
route length (km)	700	800	800	1600
wire = route ×4×2 (km)	5600	6400	6400	12800
DC sea cable				
route length (km)	1950	2050	800	800
cable = route ×2 (km)	3900	4100	1600	1600
Material of overhead lines				
Aluminum (1000 t)	30	44	54	80
Steel, wires (1000 t)	11	16	20	30
Steel, towers (1000 t)	72	102	122	190

Non-conventional Energy Transfer

The most promising non-conventional economic mode of transport of large amounts of energy is to use hydrogen as energy carrier. It can easily be stored, transported, and re-converted into mechanical, electrical, or thermal energy.

With technology improving in the future, H_2 electrolysis is expected to convert 3.3 kWh into 1 Nm^3 of H_2 in a process requiring 0.8 kg of water [21,22]. (For comparison: hydroelectric generation of 3.3 kWh under a head of 1000 m requires 1500 kg of water. Thus 1/2000 of the turbine discharge had to go into H_2-electrolysis.) Allowing 10% of the energy generated annually in a standard glacier power scheme (31-53 TWh--see Table 7), for local consumption and conversion losses, the remaining 28-48 TWh gives an annual production of 8.5-14.5 × 10^9 Nm^3 or 0.75-1.3 Mt of H_2 gas. Transport to the consumer centers in Europe and North America can be effected in two ways:

- Transport of H_2 gas through pipelines along the routes selected for electric transmission over distances of 3500-5000 km. Transport flow per standard scheme during 8000 h is 300-500 Nm^3/s, and with an initial pressure of 65 bar, pipe diameters of 0.7-0.9 m on land or a bundle of pipes with equivalent cross section across the sea are needed. Pressure must be maintained by relay compressors every 500-1000 km [23]. Total compressor power for a 4000 km pipeline is 100-140 MW, and energy consumption during 8000 h amounts to 800-1100 GWh--3% of the transported energy. Pipelines in shallow water are already being used for oil transportation from off-shore wells where the bottom is less than 200 m below sea level. A trunk line between Tunis and Italy has been planned to reach water depths of 650 m, and a maximum depth of 360 m has been reached by a pipeline crossing the Strait of Messine [24]. For pipelines crossing channels of 1000 m and more depth we face the problem already mentioned for sea cables: pipes laid on the sea bottom may hardly be recovered in case of faults, and for floating pipes an adequate technology has still to be found and tested. Pipeline weights for a trunk line carrying the equivalent of 5 GW over each of the four routes, with 50% weight addition for transocean lengths, are

$$0.76\text{-}1.21 \times 10^6 \text{Mt of steel for route Ia}$$

$$0.89\text{-}1.43 \times 10^6 \text{Mt of steel for route Ib}$$

$$0.66\text{-}1.05 \times 10^6 \text{Mt of steel for route IIa}$$

$$0.91\text{-}1.46 \times 10^6 \text{Mt of steel for route IIb.}$$

This is about ten to twenty times the steel requirements of an electric transmission system of the same capacity.

     - By liquefaction, the volume of hydrogen is reduced to
       1/800 of the gas volume, the density of liquid H_2
       being about 70 kg/m^3 [21]. With present technology
       and plant size, the liquefaction process absorbs 27%
       of the energy input [25]. In the future, advanced
       large-scale plants might be operated with not more than
       15% energy loss. Liquid hydrogen can be transported
       to ports in Europe or North America, and even to ports
       further from Greenland, by special tankers. For a 5 GW
       standard scheme, the annual transport weight of liquid
       H_2 including containers will not exceed 1-2 Mt. Two
       tankers of 50-100,000 t loading capacity each could
       service a standard power scheme of East Greenland with
       10 hauls a year during the ice-free summer and fall
       months.

Transportation Losses of the Various Transportation Modes

    EHV transmission will have to be managed in such a way that
transportation losses do not exceed 10%. Loss estimates in
hydrogen transportation are less simple. Conversion of electric
energy into H_2 is expected to develop to an overall efficiency
of almost 100%, and an assumption of 95% efficiency might be
assumed [22]. Transportation losses of the pipelines consist
of the energy consumed by the compressors. Liquid hydrogen
requires higher conversion losses while propulsion energy of
the tankers including the empty back-haul constitutes a trans-
portation loss of less than 1% of the transported energy. Re-
conversion of H_2--gas or liquid--into electric energy in con-
ventional thermal power stations or gas turbines should be
precluded in view of the low efficiency. Reconversion is
justified only if advancing technology allows for large-scale
application of fuel cells with an efficiency of at least 70%
[27], or of hot-shot gas turbines as developed by General
Electric [26].

    The breakdown in Table 10 allows the energy flow and losses
from the glacier power station in Greenland to the gross markets
in Europe and North America for each mode of transport to be
traced (distribution in the market region excluded).

Large-scale Energy Use on Greenland?

    In addition to minor energy supplies to domestic industries
processing yet unknown natural resources of Greenland, establish-
ment of energy-intensive industries on adequate coast sites could
be envisaged. Three options have been considered, namely produc-
tion of methane, ammonia, and aluminum.

     - Production of methane or another synthetic fuel has to
       be excluded since Greenland geologically belongs to the
       Caledonian Shield which is known to be poor, if not

empty, of coal. If coal from North America or the British Isles were to be used, it might be more economic to transport H_2 from Greenland to the mining area than coal to Greenland.

Table 10. Predicted yearly energy flow and losses.

Transport by:		EHV	H_2 gas	Liquid H_2
Energy generated	(TWh)	31-53	31-53	31-53
Supply to Greenland	(%)	5	5	5
Energy for export	(TWh)	29.4-50.4	29.4-50.4	29.4-50.4
Conversion loss	(%)	5	5	15
Energy converted for transport	(TWh)	27.9-47.9	27.9-47.9	25.0-42.8
Transport loss	(%)	10	3	1
Energy arriving in consumer region	(TWh)	25.1-43.1	27.0-46.5	24.7-42.3
Conversion loss, electric use (H_2 via fuel cells)	(%)	-	30	30
Electric energy available	(TWh)	25-43	19-33	17-30
Total loss	(%)	19	38	44
Conversion loss, thermal use	(%)	5	5	5
Thermal energy available	(TWh)	24-41	26-45	24-40
	(10^6Gcal)	21-35	22-39	21-34
Total loss	(%)	23	16	24

- Production of ammonia as an energy carrier or a raw product for the fertilizer industry is another option since cheap energy, water, and air are available in Greenland. Although the use of ammonia as an energy carrier seems not well accepted [28], the world market's capacity of 80 Mt of ammonia per year is increasing by 10% p.a. A Greenland standard scheme of 5 GW could produce 5-6 Mt of ammonia per year to supply the market. However, the fertilizer industry appears to have free capacities in some regions, and ammonia production is a favored goal of national development in most of the developing countries.

- Production of aluminum seems most promising within limits dictated by the market. Long-distance transportation of bauxite is not new: Australian bauxite is being used in the large aluminum factories of the US and Canadian Pacific coast. Considerable quantities of bauxite will in future be marketed by Brazil and equatorial Guinea [29], both regions being located acceptably near Greenland. With a consumption of 16 kWh/kg aluminum and the low generation cost of the glacier power, aluminum production on Greenland would have energy costs of 75-100 US-$/ton which would more than compensate for higher transport charges of the raw material and the final product. The price of Greenland aluminum is expected to be 600-700 $/t--competitive with the output of existing plants with higher energy costs. Limits will be posed by the quantities of bauxite available from the two expanding suppliers mentioned: they will hardly exceed 25 Mt a year, equivalent to some 5 Mt of aluminum, and this production would absorb 80 TWh--10-20% of the Greenland energy.

Construction Schedule and Costs

Construction Schedule

Development of Greenland's glacier power resources calls for thorough preparatory investigations and studies, surveying and mapping, collection of hydro-meteorological data, test programs, etc., for which a period of 5 years (say 1980-85) is a minimum. Another 5-year period (1985-90) must be spent on development planning and design, along with preparatory field work such as access, housing and supply facilities, airfields, ports, cableways, and other traffic facilities. Construction of the first power scheme should be started on the west coast where conditions are more favorable than in the east, and must not be scheduled earlier than 1990. Construction of each power scheme may take 5 to 6 years. From experience in implementing the first scheme, construction of two schemes at a time with 2-3 years' overlapping seems feasible. This will result in a continuous construction period of 40-50 years (1990-2030/40) for a total of 15 schemes.

Cost of Power Schemes

The main construction requirements and costs of a standard power scheme are roughly estimated as follows:

Site installation	200-300 M$
Collectors: $50-80 \times 10^6$ m^3 at 2-2.5 $/m^3	100-200
Reservoir dams: $5-10 \times 10^6$ m^3 at 10-15 $/m^3	50-150

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Tunnels:   8-15 km at 4000-5000 $/m                    35-75

Penstocks:  excav. 100-250,000 m³ at 50 $/m³
            + steel 40-70,000 t at 1600 $/t          70-125

Power stations 4-6 GW:
            civ. engr. 1-1.5 $/kW                      5-10
            mech.-elec. equipment 65-80 $/kW         320-520
```

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                        Subtotal                    780-1380 M$
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Plus 40% for contingencies, planning,
     overheads and financing costs                  320-550
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Total of a standard scheme                         1100-1930 M$
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Specific construction costs per power and energy units amount to 275-320 US-$/kW installed, or 3.5-4 cents/kWh of annual energy output, both rather low values which, however, have been approximately achieved in some recent Canadian power developments. Owing to the high maintenance and salary costs under the specific difficulties in the ice region, generation costs might be adopted at 12-15% of the construction costs instead of the 10% rate under normal conditions of hydropower stations. Hence generation costs in Greenland might be expected at 4.5-6 mills/kWh.

Cost of Energy Transportation--Electric Transmission

Each EHV standard system carrying 10 GW (80 TWh per year) is able to transfer the energy generated by two standard power stations. Construction requirements and costs of an EHV system along each of the four transmission routes to Europe or North America are presented in Table 11. The estimate of cable costs is based on the expectation that production of large quantities of EHV sea cables over a period of 40 years will decrease unit costs far below the present price level to about 4 times the overhead line price now valid for normal 110 and 220 kV systems. Unit prices are related to the route length and refer to double-circuit overhead lines and double sea cables.

Specific investment increments for EHV transmission are 310-430 $/kW or 4-5.5 ct/kWh for Europe, and 220-300 $/kW or 2.5-4 ct/kWh for North America. With annual running costs of 15% of investment, transmission costs to Europe amount to 6-8 mills/kWh, and those to North America to 4-6 mills/kWh.

Table 11. Costs (M$) of electric transmission.

Route	I a	I b	II a	II b
AC overhead at 400 $/m	360	580	760	1040
DC overhead at 300 $/m	210	240	240	480
DC sea cables 1200-1600 $/m	2340-3120	2460-3280	960-1280	960-1280
Converter stations 10 GW at 20 $/kW	200	200	200	200
Total	3110-3890	3480-4300	2160-2480	2680-3000

Cost of Energy Transportation--Hydrogen

Investments and costs of energy transfers from each 5 GW-
standard power scheme with hydrogen gas have been tentatively
estimated based on reference data of future H_2 electrolysis from
La Roche [25] and General Electric [26], and of pipelines from the
EURATOM publication [23] with control by EdF figures [30] (Table 12).

Table 12. Costs (M$) for hydrogen transportation.

Route	I a	I b	II a	II b
H_2 electrolysis 4-6 GW at 30-50 $/kW	120-300	120-300	120-300	120-300
Pipelines on land 250-300 $/m	400-480	560-680	670-810	1050-1260
Sea pipelines 500-600 $/m	1000-1200	1000-1200	400-480	400-480
Total	1520-1980	1680-2180	1190-1590	1570-2040

No satisfactory reference data have been found for sea pipelines.
Specific cost data of more than 1000 $/m for 92 cm (36 inch) pipe-
lines in the North Sea oil field have not been regarded as repre-
sentative for future sea pipelines over many thousands of kilo-
meters. Initial costs today in the North Sea with pipelines of
about 100 km only are certainly inflated by development and pioneer
costs that will soon disappear when off-shore oil production and
transport lines increase. A tentative assumption of twice the on-
land costs has been adopted.

Related to the power and energy units of the standard power
scheme, the additional transport investments for H_2 pipelines

make up for 320-400 $/kW or 4-5 ct/kWh to Europe, and 300-340
$/kW or about 4 ct/kWh to North America. Conversion and transport
costs to the European gas market amount to 6-7.5 mills/kWh input,
and those to North America to about 5 mills/kWh.

These estimates show that transmission costs of electric
energy on EHV lines and those of hydrogen by gas pipelines are
about equal. This is an interesting result since several authors
have suggested that over distances of more than 400 km hydrogen
transportation is much cheaper, down to one-tenth of the cost of
electrical transmission [21,31]. Other authors fully support our
result and have suggested that for distances of 1000 km or more,
transportation costs with EHV or H_2 gas pipelines are more or
less equal [30,32].

Reconversion of H_2 into electrical energy via fuel cells
needs an additional investment of 350-530 M$ based on specific
costs of 100 $/kW [31]. Incremental generation costs in the fuel
cell plant will be 1.5-2 mills/kWh.

In hydrogen liquefaction, investments consist of the lique-
faction plant roughly 600-900 M$ (150 $/kW) for the standard
glacier power scheme [33], and of two special tankers for liquid
H_2 transportation which might cost some 50 M$. Operating and
amortization costs of the liquefaction plant are 2.5-3 mills/kWh
while transportation costs by tanker over some 4000 km are about
2-3 mills/kWh.

EVALUATION AND INTEGRATION INTO A FUTURE GLOBAL ENERGY SYSTEM

General Evaluation

Although cost estimates at this preliminary state of know-
ledge and planning include a considerable number of uncertainties,
we have no reason to doubt that Greenland's glacier power, if at
all feasible, is a very cheap source of energy. However, it is
located far from potential energy markets, and its cost to the
consumer will result from transportation and production costs,
whatever mode of transportation is selected. This may render the
Greenland energy economically less competitive than conventional
power sources in the consumer regions of Europe or North America.
The more so since only large-scale development is to be envisaged
from the very beginning. An input of 5 GW at one point of the
existing transmission grid constructed to link a number of de-
centralized supply stations of the order of little more than
1 GW might cause additional distribution problems especially in
Europe. North America has already several schemes of approximate-
ly the same power capacity as the standard scheme envisaged on
Greenland.

In evaluating the Greenland energy, however, not only eco-
nomic terms have to be considered. Hydropower resources still
available today in the North Atlantic countries will most prob-
ably be fully developed by the year 2000. Development of

Greenland's glacier power is an opportunity to continue tradi-
tional hydropower engineering and manufacturing for another half
century, and to postpone the target date of inactivity of many
substantial branches of industry. It would also continue to make
profitable use of the advantages of hydropower in relation to
conventional thermal or nuclear energy, namely:

- Longer lifetime of the power plant (80 years instead of
  30 years, except machinery);

- Low production costs even under the severe maintenance
  conditions to be expected in the collector systems on
  the ice cap. Since production costs are predominantly
  determined by the annuities for external loans, and
  independent of rising fuel prices, they respond much
  more favorably to inflation and decrease to an almost
  negligible level after the amortization period;

- Independence from unstable and sometimes unreliable fuel
  supply conditions;

- The ecological advantage of using an inexhaustible,
  continuously renewed natural energy source without
  changing its quantity or quality, and with no harmful
  impacts such as air, water, or thermal pollution, radia-
  tion risks, or waste disposal.

Options for Energy Transfer from Greenland

Decision on the appropriate system for energy transfer from
Greenland depends on cost criteria as well as on general consider-
ations of the particular systems and of the market conditions.
Figure 7 provides a survey of the options. They may be summarized
in two scenarios: a pure electrical one, and a mixed electrical-
hydrogen one.

Scenario A: A Pure Electrical System

A combined DC-AC link of EHV overhead lines and sea cables
seems feasible and promises some advantages as to transport
loss and consumer costs if it is electrical energy that is
wanted. This scenario deserves priority if sufficient storage
reservoirs can be made available to warrant year-round full-load
generation (8000 h variant). It may also be adequate in cases
of restricted reservoir facilities and rated generation periods
of 6000 or 4500 h per year, if this period is more or less equally
distributed over the year with intermittent full-load or even
temporary part-load generation of say 12 or 16 h a day, at no
extra cost for this peak load supply. (Peak load generation in
a 8000 h plant would call for larger tunnel and penstock dimen-
sions, and higher capacity installed in power station and trans-
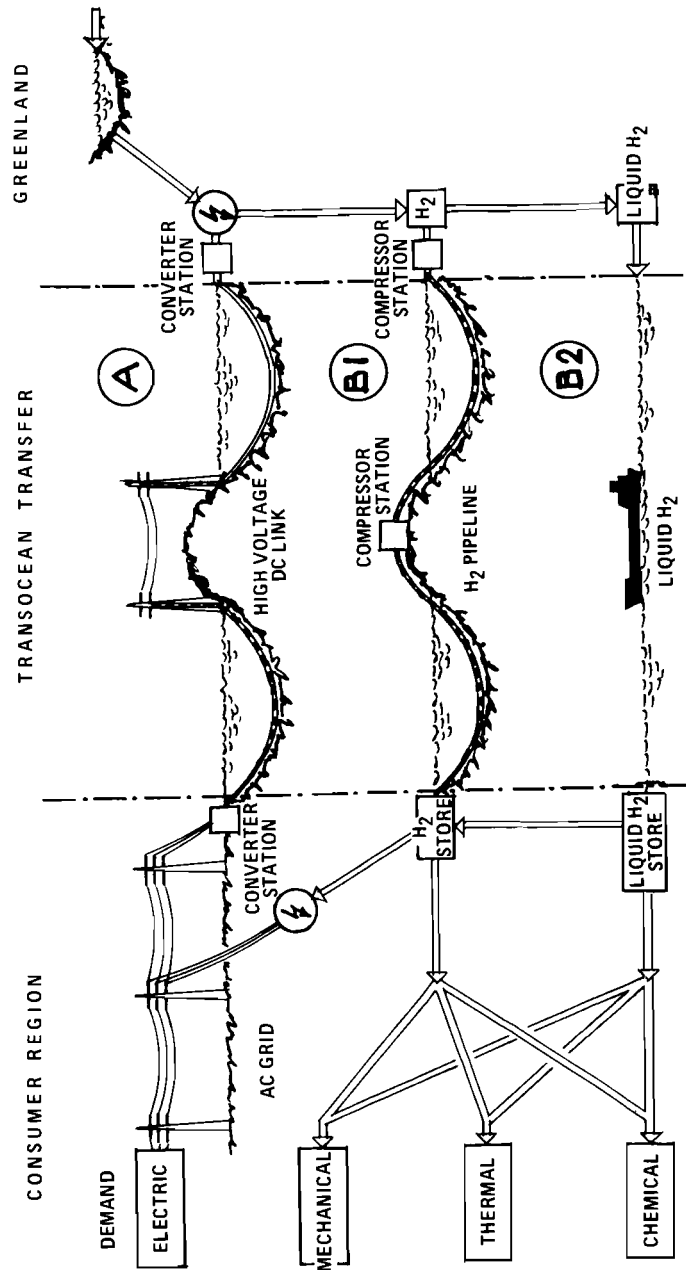mission line at remarkable surplus cost which must be borne by
higher earnings).

Figure 7. Options for transportation and use of the Greenland energy.

Scenario B: A Mixed Electrical-Hydrogen System

Electrical energy generated on Greenland goes directly into H_2 electrolysis and is transferred to the consumer regions either by pipelines carrying H_2 gas (Scenario B 1) or by tankers carrying liquid H_2 (Scenario B 2).

Scenario B 1 will reach its optimal economic value if, like scenario A, power generation with full load is warranted all year round.   It will be competitive if markets for gas, thermal energy, or chemical processing exist in the consumer region, since reconversion into electrical energy either in gas turbines or in the boiler or a conventional thermal power station has a very low efficiency (35%).   Fuel cells with an expected higher efficiency of 65-70% or hot-shot gas turbines would be more adequate but their technology is still to be developed and a large-scale application is not yet in sight [27].

Scenario B 2 suffers from higher conversion losses for liquefaction but might be an adequate solution for those power schemes in the east of Greenland where storage reservoirs are hardly to be found and power generation will be restricted to a maximum of perhaps 6 summer and fall months.   This period is also the only time of the year when tankers will find access to the loading ports of liquid H_2 near the power station and liquefaction plant.   In the consumer region, liquid H_2 can easily be stored for continuous sales.   The scenario is handicapped by long idle periods--certainly not an ideal solution for large investments but still acceptable under the special conditions of some parts of Greenland.

Energy Costs to the Consumer

These depend on the final application of the energy from Greenland.   If it should be electrical energy for every scenario, costs in US-mills per kWh available in the consumer region are assessed in a preliminary way as shown in Table 13.

Table 13.

	Sc. A	Sc. B 1	Sc. B 2
Generation on Greenland	4.5-6.0	4.5-6.0	4.5-6.0
Conversion and transport	4.0-8.0	5.0-7.5	4.5-6.0
Reconversion into electricity*	–	1.5-2.0	1.5-2.0
Net cost, consumer region	8.5-14.0	11.0-15.5	10.5-14.0
Energy losses*,** (%)	19%	38%	44%
Equivalent surcharge	1.5-2.5	4.0-6.0	4.5-6.0
Cost of available energy	10-16.5	15-21.5	15-20

*With fuel cells adopted.
**See "Power Application and Transfer" section.

For thermal application, equivalent costs in US-$/Gcal are as shown in Table 14.

Table 14.

	Sc. A	Sc. B 1	Sc. B 2
Generation on Greenland	5.25-7.0	5.25-7.0	5.25-7.0
Conversion & transport	4.75-9.5	5.75-9.0	5.25-7.0
Net cost, consumer region	10.0-16.5	11.0-16.0	10.5-14.0
Energy losses	23%	16%	24%
Equivalent surcharge	2.5-4.0	2.0-2.5	2.5-3.5
Cost of available heat	12.5-20.5	13-18.5	13-17.5

Tentative Development Model of Greenland's Glacier Power

Each scenario has its merits in production facilities, transmission advantages, and consumer market conditions. The market for large quantities of electrical energy will be found more easily in North America where also the transocean distance from Greenland is shorter. Both facts are in favor of scenario A. Most of the glacier power generated all year round in the schemes of Western Greenland will suit this option.

Existing oil and gas development in the North Sea by its bordering countries obviously favors scenario B 1. Glacier power in South Greenland may be regarded as a natural source of H_2 gas supplies to Europe extending the fuel supply from the North Sea beyond the date of their exhaustion.

Scenario B 2 is adequate for the less favored glacier power schemes of Eastern Greenland with intermittent operation periods and standstill during winter and springtime. Tanker transportation of liquid H_2 can be to any port of the North Atlantic and even further south if market conditions warrant it.

These conditions, together with the adopted standard capacities of 10 GW for a double-circuit EHV transmission link and of 5 GW for an H_2 gas line, induce a diversification of Greenland's glacial power according to the model illustrated in Table 15. This model must not be taken as final; it is just one particular development idea picked out of many possible ones. It may serve as an indicator, and is used as a basis for the considerations on investment, material, and other requirements that follow.

Table 15. Tentative Development Model (75 GW).

Scenario	Supply to	Power (GW)	Transport systems per route	Quantities supplied to consumer regions per year
A	Europe	10	1 × I a 1 × I b	50-85 TWh electricity
A	N. America	30	2 × II a 1 × II b	150-250 TWh el.
B 1	Europe	15	2 × I a 1 × I b	$25\text{-}43 \times 10^9$ Nm^3 H_2 gas
B 1	N. America	10	1 × II a 1 × II b	$17\text{-}43 \times 10^9$ Nm^3 H_2 gas
B 2	Atlantic	10	Tankers	1.5-2.5 Mt liquid H_2

Integration Into a Global Energy System

The parameters used by IIASA to evaluate an energy source and integrate it into the world economy are [35]:

- amounts of reserves and resources;

- requirements of land, material, equipment, labor force, and capital;

- global transport problems; and

- possible constraints.

Greenland's glacier power is now analyzed with regard to the first three parameters, while constraints are dealt with later.

Reserves and Resources

In IIASA's global energy program, future world energy demand of a population of 12×10^9 is estimated at 24-60 TW. Compared with this, an energy flow from Greenland of 50-90 GW has an insignificant share. In any decision on future energy options and strategies, hydropower is just of local or regional importance. In the near future, however, hydropower inputs are welcome, and in this time scale Greenland's glacier power could play a much more important role.

The Nuclear Research Institute at Jülich, FRG, recently published a survey of energy resources [36]. It includes an estimate of hydropower resources of the world based on assessments of the World Energy Conference and the regional economic

commissions of the United Nations, with a breakdown by continents and by three levels of potential:

E_o, theoretical potential derived from the total discharge of an area over the entire available head (comparable to the hypothetical reserves of the McKelvey resources diagram);

E_{to}, technically feasible potential, including non-economic reserves;

E_t, economically feasible potential (comparable to McKelvey's known and explored resources).

Table 16 expands the values offered by the Jülich Institute by adding the values for Greenland (all in TWh/a):

Table 16.

Region	E_o	E_{to}	E_t
Africa	10,118	6832	3604
Asia (incl. Asian USSR)	16,486	7253	3192
Europe (incl. European USSR)	4,358	2450	953
Latin American	5,670	5054	3276
North America	6,150	2742	1409
Austrialia and Oceania	1,500	744	470
World	44,282	25,075	12,904
Greenland	3,000	1000-1300	460-800

Land Requirements

The land requirements of the glacier power schemes are modest even if one includes the land inundated by reservoirs on ice-free ground which in fact can be utilized like every natural water surface. Comparable hydropower schemes in the Alps have a permanent land requirement of 0.3-1 ha/MW, an almost negligible land occupancy for construction facilities, and no land claims for fuel production. Reference data for other types of energy sources have been assessed by Grenon [38]:

- Solar power plant   3 ha/MW permanent

- Coal-fired thermal plant 0.5-2.5 ha/MW incl. strip mining over 25 years

- Nuclear power plant   0.8-3.7 ha/MW incl. strip mining over 25 years.

Material Requirements

The main items of construction material for the development of the Greenland energy and its transportation facilities are:

- cement and steel for the power stations,

- steel and aluminum for electric overhead lines,

- electric cables, and

- steel for gas pipelines.

Compared with these bulk quantities, requirements in other categories of the Kononov economic model [37] such as nonferrous metals and fabricated metal products, plastic, and synthetic materials, or wood and paper are unimportant.

Based on the "Tentative Development Model" outlined, each gigawatt of installed capacity requires the amounts of material shown in Table 17.

Table 17.

Material		Power Station	EHV lines	Gas lines
Cement	(1000 t/GW)	25	.	.
Steel, construction mechanical and	(1000 t/GW)	15	7	85
electrical equipm.	(1000 t/GW)	20	1	.
Nonferrous metals	(1000 t/GW)	.	4(Aℓ)	–
EHV cables	(km/GW)	–	170	–

Total requirements for the tentative model of nominally 75 GW are Table 17's figures multiplied by 75. Over the construction period of 40-50 years, average annual demands are about 1.5-2 times the indicated figures. Individual development steps will of course differ more or less from the indicated amounts.

Other material parameters introduced by Grenon [37] are the weight of the station, and the total flow of material including fuel. The weight of the power station is understood as the total weight of elaborated materials used for the construction, in the case of hydropower this being cement and steel. The flow of material is defined as the quantities of raw material (but not of overburden) moved for fuel production in the case of a coal or nuclear plant, and that handled for the production of the heliostats in case of a solar power plant. Following these definitions, the material flow of a hydropower plant would be almost zero, since it needs no fuel and has no large material requirement other than concrete, earth and rock excavation, or

dam fill, which have to be excluded for true comparison to the
Grenon values. Hence two relevant values are given in Table 18
with the intention to add reference data for a glacier power
station of 1 GW to the Grenon table: values following the defini-
tions, and in brackets higher values including the above mentioned
main components of hydraulic engineering.

Table 18.

1 GW station	Weight of station (10^6 t)	Total flow (10^6 t)	Comments
Coal fired	0.3-0.35	50	25 years
Nuclear (LWR)	0.5-0.6	2.5-75	U 2%-U shale 25 years
Solar	0.3-3	1-12	5-7 years
Glacier power	0.1	0.5-1 (4-15)	5-6 years

Equipment Requirements

These are of two categories: mechanical and electrical
equipment installed in the power stations and transmission
facilities, and equipment and machinery used for construction.

- It has been pointed out that turbines, generators and
  other equipment of the glacier power stations are not
  different from those used today in large hydropower
  schemes all over the world, perhaps with some evolution
  but certainly with no innovations needed. Manufacturing
  of such equipment of the order of some 1.5 GW per year
  over the construction period of 40-50 years will cause
  no change in the relevant manufacturing industry, and
  will be easily absorbed once the conventional consumer
  market ceases on completion of the on-going hydropower
  development in most of the North Atlantic countries.
  The extraordinary requirements for transmission facil-
  ities, however, will call for new production industries
  at least in the field of EHV sea cables which today are
  confined to lower voltage levels and to an order of
  100 km and less. In this field, new technologies and
  a new industry have to be established with a production
  capacity of 200-300 km of EHV sea cable per year. Sea
  pipelines, on the other hand, exist already now with the
  deployment of off-shore gas and oil resources everywhere.
  A relevant industry will expand even without the Greenland
  option, and will most probably appreciate a market for
  their goods continuing beyond the limited time of the
  North Sea boom.

- New types of building equipment in large quantities will
  be needed for ice engineering, and part of this equipment
  will stay in permanent use for maintaining the collector
  canals on the ice cap. All other equipment for the con-
  struction of tunnels, penstocks and power stations, port
  and traffic facilities, and overhead EHV or pipelines
  will be met by the present rate of production. A few
  special vessels for sea cable or sea pipe laying will
  have no importance in any global production or trade
  model.

Labor Force and Energy Requirements

Hydropower development over the last 25 years has been
characterized by a sharp decline of manpower on the construction
sites due to the progress of energy-consuming mechanization.
Reference data for Austrian hydropower stations show a drop from
500-800 man-months per installed megawatt to below 100 man-months/
megawatt, although no pronounced correlation of manpower with
installed capacity was evident. A labor force of 2000-2500
workers including the planning, assembling and control staff
would seem a natural limit for a large construction site. With
two schemes under construction at a time, a labor force of
4000-5000 people will be needed continuously for implementation
of the Greenland project. Manpower for each standard scheme
with 5 to 6 years construction time amounts to 100-150,000 man-
months--equivalent to only 25-30 man-months/megawatt.

The less manpower, the more mechanization is needed. Recent
experience at various hydropower construction sites is that the
peak demand of construction equipment in mechanized horsepower
is numerically equal to, or a bit less than, the total number of
man-months accumulated at this site. For hydropower plants smaller
than 100 MW, maximum demand may go up to twice the number of man-
months. Hence construction equipment with a peak motor power of
100-120,000 hp (75-90 MW) will have to be installed at each site
while the average demand will be 65-80,000 hp (45-60 MW). Fuel-
driven and electrical equipment will have approximately equal
shares. The total requirement of construction equipment for the
Greenland project with two overlapping construction sites running
at a time amounts to 150-180,000 hp (112-135 MW).

Energy consumption of the Greenland construction sites will
be higher than that of conventional hydropower sites, due to the
arctic climate causing a considerable heating demand all year
round. Electric energy consumption may amount to 20,000 kWh per
capita and year totalling at 200-300 GWh for each power scheme,
not including energy extras which might be needed for artificial
heating in ice engineering. Fuel driven equipment will consume
$20-25 \times 10^6$ liters (125-160,000 barrels) of fuel for the con-
struction of each standard glacier power scheme.

Capital Requirements

The "Energy Impact Model" developed by IIASA in cooperation with the Siberian Power Institute of the USSR Academy of Science works with direct as well as indirect investment requirements. The categories of this model are the basis for the following breakdown of approximate investment requirements of the 75 GW Tentative Development Model of Greenland energy (Table 19).

Table 19.

	Investment totals direct (10^9 $)	indirect (10^9 $)	Annual Investment Rates direct (10^6 $)	indirect (10^6 $)	Period (years)
Power schemes	21.5	-	480	-	45(6-50)
H_2 electrolysis	2.0	-	50	-	40(11-50)
H_2 liquefaction	1.5	-	50	-	30(21-50)
EHV transmission	15.0	-	430	-	35(6-40)
New cable industry	-	0.5	-	100	5(1-5)
Gas pipelines	8.5	-	270	-	30(11-40)
Liquid H_2 tankers	-	0.1	-	20	5(21-25)
Total	48.5	0.6	1280 max	.	20(21-40)

Global Transportation Problems

Transportation of Greenland energy to the consumer regions over distances of 4000 km poses virtually the same problem as other energy options envisaged for the future, e.g. large-scale solar power developments in the Sahel region or a nuclear power pack (the "energy island") in the Pacific or any other remote place [39]. However, there is a big difference in the order of magnitude which is some 75 GW in the case of Greenland versus several terawatts of the energy island. Even the present flow of oil from the Middle East of 1.7 TW is much higher than the future power flow from Greenland.

Transportation of construction material and equipment from production facilities in Europe or North America to Greenland will influence construction costs, but an additional volume of 150-250,000 t a year will pose no problem on world traffic. The same is true for placing orders on perhaps four medium size special tankers for the transport of liquid H_2. A minor problem could arise from the requirement of aircraft for dispersing darkening substances on large ice areas in order to accelerate melting.

Evaluation of Constraints

The analysis of possible constraints affecting the develop-
ment of Greenland's glacier power follows six categories which
have been established by IIASA for the evaluation of a new
energy source [35].

- Market penetration is no problem since the Greenland
  project just extends conventional hydropower over another
  half century in supplying established markets for electri-
  city or gas in developed countries which are in need of
  energy imports.

- No new standards have to be fixed since most technologies
  to be applied are well advanced, and only a few categor-
  ies such as ice engineering or sea cables need further
  steps of evolution.

- No change in infrastructure will take place except the
  establishment of settlements and traffic facilities on
  Greenland. Both electricity and gas dispose of an estab-
  lished industrial infrastructure with a considerable rate
  of expansion.

- Capital constraints might arise if the Greenland energy
  had to be developed by Greenland or Denmark on their own,
  but if a joint multilateral development took place, a
  capital requirement of the order of 10^9 US-$ per year is
  no limiting factor. The disadvantage of higher specific
  investment needs of some 600 $/kW including transmission
  is compensated by low operating costs, even with extra-
  ordinary costs for maintenance, and by the lack of any
  fuel expenses.

- Ecological impacts have to be studied carefully but on
  a first preliminary judgment no impacts of global impor-
  tance should be expected from the change of the glacier
  regime by the energy development. It has been stated
  that perhaps 100-200 km^3 of ice mass will be tapped
  annually in excess of the present conditions by increased
  melting. This is not only negligible against the total
  volume of Greenland's ice mass of 2,600,000 km^3 but also
  it is within the limits of natural variations of accumula-
  tion and ablation, estimated by different authors at
  between +295 and -84 km^3 per year [36]. Local impacts
  in the development area of Greenland may emerge from
  additional glacier ablation accumulating over 100 years
  to a total of 50 m out of a mean ice thickness of 1500 m,
  and from an additional supply of warmer water from the
  reservoirs to the surrounding ocean of the order of
  100 GW as against a heat transfer by the Gulf Stream of
  660 TW. The water table of the oceans will react only
  insignificantly to the additional melting discharge by
  a cumulative rise of 3-4 cm over 100 years.

- Risks exist with regard to the technical and economic
  feasibility and the performance of the collector system

on ice, but hardly with regard to the human environment. Glacier power has no emissions, no waste, no hazards--especially in a thinly populated area like Greenland where even such low probability risks as a dam failure, or bursting of an ice dam or channel will have insignificant detrimental effects. Nor could the failure of a sea pipeline carrying pure hydrogen have polluting or poisoning impacts. Local impacts around the electrodes of the DC sea cable terminal can be met by adequate protective devices. Potential impacts on fish and limnology in the fjords where turbine outlets discharge warmer water throughout the year can be advantageous as well as disadvantageous and have to be studied.

Summarizing the above considerations, one should not expect any serious constraints of an economic or ecological nature which might prohibit the development of the Greenland energy if it proves to be technically feasible.

FURTHER STEPS TOWARDS A DEVELOPMENT OF THE GREENLAND ENERGY

It is hoped this study will serve to create a broader interest in more profound studies on Greenland's glacier power by the governments or energy administrations of the North Atlantic border states concerned by and involved in the development, by the Danish authorities responsible for the administration of Greenland, and by international organizations such as the United Nations in its Center of Natural Resources, Energy and Transport (CNRET) of the Economic and Social Council, or UNESCO and WMO.

The study program could consist of an intensified collecting of basic scientific data, and a more practicability-oriented test and investigation program including the new technologies to be developed. A tentative--certainly not complete--list of topics for a study program is outlined here.

Basic Information and Data Collection

- Collection and study of ERTS photos of South Greenland for an overall survey of snow cover and ice conditions in all seasons.

- Aerial photography of the ice cap and surrounding mountain ridges down to the ocean, south of 72° N in the west and of 69° N in the east.

- Topographic surveying of border zones of the ice cap and surrounding mountain ridges in selected areas, in specific test areas.

- Establishment of climatological stations (temperatures of air, snow, ice, and water; wind; precipitation; sunshine and radiation; albedo) on the ice cap up to 2000 m.

- Observation of snow, firn, and ice behavior in the soak-
  ing and ablation zones; data collection for estimating
  water yields.

- Study of the ecological impacts of increased melting
  with regard to the glacier regime, global weather condi-
  tions, ocean currents, ice drift and pack ice, water
  and air temperatures and local climate; data collection
  for quantifying such impacts.

- Identification of climatic consequences of an albedo
  change by the artificial darkening of large ice areas.

- Exploration of permafrost occurrence in areas where con-
  struction activity might be expected.

- Selection of an easily accessible test area where glacier
  power development seems most promising, and intensified
  observations there.

Preparatory Technical Investigations and Tests

Topics for the technical study and testing program prior to
the planning and design phase of the first power development are:

- Investigation of the melting process and of appropriate
  methods to collect melting waters and to keep them from
  refreezing.

- Testing of heat-absorbing substances and materials such
  as dark sand, fly ash, PVC lining, and their accelerating
  effect on melting, and an estimate of the technical and
  economic feasibility of their large-scale application.

- Investigation of ice properties in view of its proposed
  use as a construction material for collector canals or
  reservoirs; tests of watertightness, roughness, and
  stability.

- Construction of a prototype collector canal on the ice
  cap, comparative tests of construction methods and equip-
  ment such as excavation by bulldozers or snowmills, and
  forced melting by motor exhaust, electric resistance
  heating, or nuclear waste containers.

- Observation of the behavior of the prototype canal, its
  resistivity to ice movements, an estimate of the amount
  of maintenance work, a study of maintenance equipment and
  methods.

- Test borings in permafrost rock, observation of ground
  temperatures around the borehole with and without water
  flow in various seasons.

- Testing of resistance of building materials and tunnel linings (concrete, steel and others) against permafrost.

- Exploration of favorable coastal sites for large-scale power stations and industrial accessories, with acceptabl(access from the sea and to the glacier region.

- Exploration of reservoir sites in the mountain valleys bordering the ice cap, and on ice where other sites do not exist.

- Calculation of flood wave risks stemming from failures of main collectors or reservoirs in the ice.

- Research on the development of hydraulic turbines for high head, flow, and capacity.

- Intensified research on EHV sea cables, and a study of methods for crossing ocean channels of great depths down to 1000 m and more.

- Intensified and specified research on the components of the hydrogen scenario.

- Study of fresh water supply from Greenland to regions of high water demand, prototype tests of long-distance transportation of large quantities of pure fresh water available from the turbine discharge.

A comprehensive study program like this will depend on the close interdisciplinary cooperation of experts of glaciology, physics, civil engineering, mechanics, electric and mechanical manufacturing, transportation, and others. Some tests might be done outside Greenland under similar but less severe climatic and environmental conditions such as the glaciers of Alaska or Norway.

With satisfactory and promising results from this study program, then planning and design can start. Decision on the construction of the first power scheme must be based on evidence of the technical and economic feasibility of the entire project.

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