Investigation Of The Viability Of A Remote Wind/hydroelectric Power Supply In The Northwest Territories

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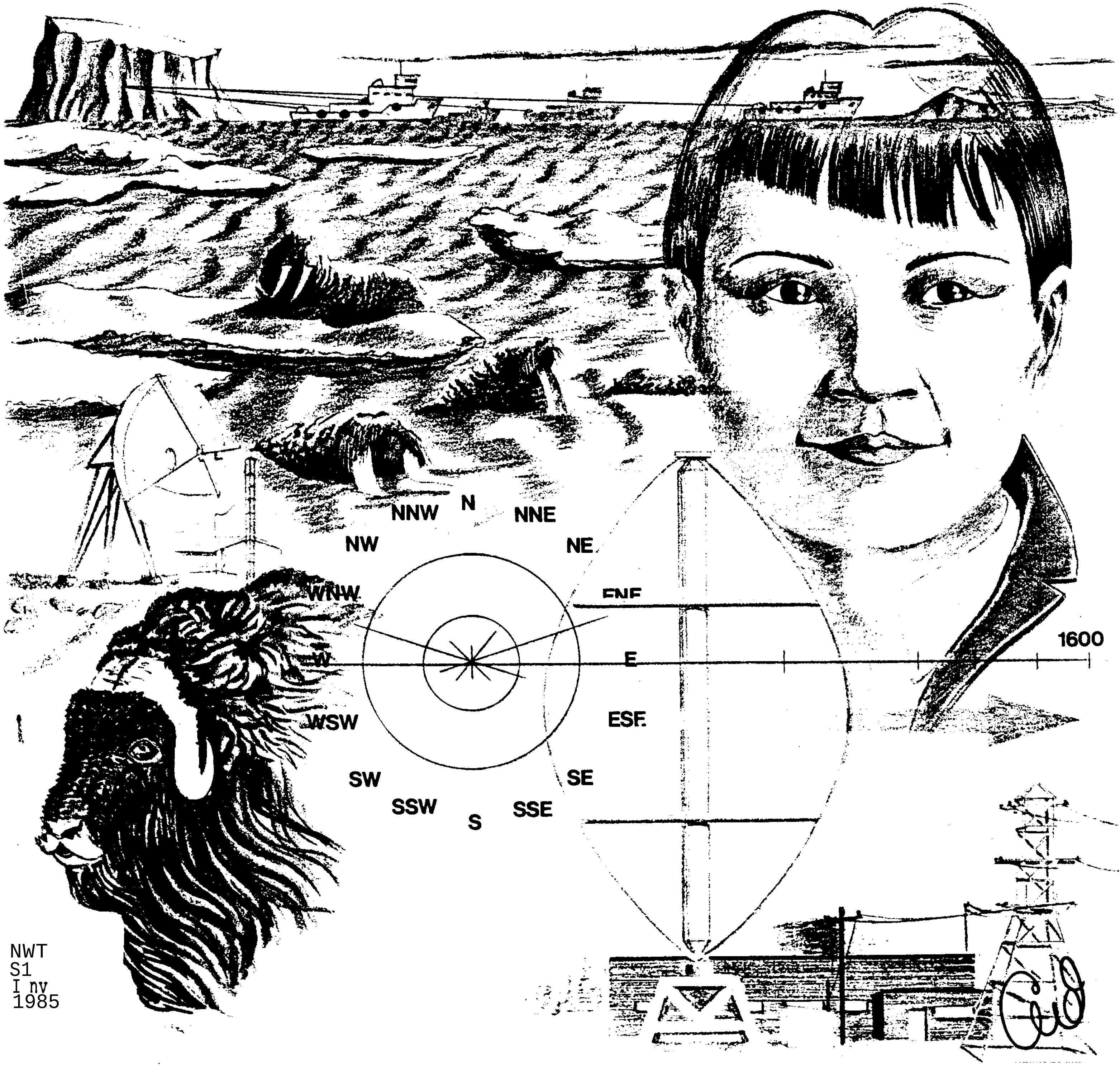

Background Study No. 1

INVESTIGATION OF THE VIABILITY OF A REMOTE WIND/HYDROELECTRIC POWER SUPPLY IN THE NORTHWEST TERRITORIES

Background Study No. 1

Prepared by:

Unies Consulting Engineers Ltd.

With a contribution from:

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EXECUTIVE SUMMARY

STUDY OBJECTIVE

This report covers the first phase of a study of which the objective is to investigate the viability of using a pumped-storage wind/hydro-electric supply system for meeting specific isolated electrical loads in the Northwest Territories. In such a systen, energy would be extracted from the atmosphere through the use of windmills or wind turbines and the load would be supplied by methods incorporating storage of water in a high-level reservoir for release through hydro-electric turbine/generators as required. For specific cases, a wind/hydro system may have the potential to replace diesel-electric generation where other alternatives are less viable.

SCOPE

In the first phase of the study the physical characteristics of a stand-alone wind/hydro system are developed. in particular, and within the perspective of possible implementation in isolated northern regions:

(a) a review of recent progress in wind-energy conversion technology is used as a basis for suggestion of potentially promising combinations of wind turbines, drives, and pumps;

(b) hydro-electric subsystem considerations are reviewed in the wind/hydro context in which the provision of firm flow for hydraulic turbine/generators is necessarily a part of the design of the wind-energy conversion subsystem; and,

(c) for conceivable stand-alone wind/hydro system configurations, the basic relationships among electrical demand, wind turbine capability, storage capacity, reservoir storage elevation, and installed hydro capacity are examined using a typical Northwest Territories wind regime and typical load characteristics.

FINDINGS OF INVESTIGATION INTO STAND-ALONE WIND/HYDRO SYSTEMS

Several wind turbine types in the 100+ kW sizes have potential for application in remote wind/hydro-electric supply systems. Design features of various lightweight horizontal- and vertical-axis wind-electric generators and low-speed, multi-bladed, horizontal-axis machines result in differences in power output among units, but other factors affecting pumping, siting, and operation of a small electricity-supply system are expected to have greater importance in wind/hydro system design. Before the most promising wind-turbine-and-pump combinations can be identified, more needs to be understood about some of these determining factors, i.e. ,

(a) the separation of mechanically linked wind turbines and pumps,

(b) operation of wind turbines at variable speeds with delivery of mechanical energy from the wind turbine rotor shaft,

(c) the effect of wind generator output power quality on the local grid, and controls to improve this quality, and

(d) performance of wind turbines and pumps in the severe northern environment.

The required understanding may be gained from further research and development, and from northern field trials.

The more favorable wind regimes near isolated communities in the Northwest Territories exhibit long-term average windspeeds which are at the low end of the operating ranges of contemporary wind turbines. Extended intervals in which average windspeeds are significantly below long-term values produce long critical periods for system component sizing (they can be on the order of weeks to months in duration). The result is a requirement for large installed nominal windpower capacity and reservoir storage capacity compared tothesize of the load.

STUDY CONCLUSIONS AND RECOMMENDATIONS

The lack of dependability in the wind as an energy source in the Northwest Territories thus would suggest that, for the isolated electricity supply systems, windpower may be more appropriately used in a supplementary or fuel-saving role. For existing or potential hydro-electric developments, firming of system energy could be effected with the use of wind- and/or diesel-electric generation to substitute for withdrawals from storage, or with the use of wind-powered pumping to augment reservoir inflows. For existing diesel-electric systems, windpower, when available, could be uses to reduce fuel consumption. As some experience has been gained already with such systems across the country (including some in the Northwest Territories), experimental-scale operation of various windpower systems in the north reasonably could be initiated and the less-understood aspects noted above could be investigated. The possibilities for use of wind turbines for remote community water supply applications could be studied at the same time.

Exploration of all avenues for maximization of unit wind-energy production is also required to hasten the economic viability of wind turbine applications in the north. The physical situation near a load centre could allow exploitation of an anomalous localized wind regime in cases where the estimated wind-energy potential for the region would have been pessimistic. Unusual wind resources which are within practical distances of communities should be identified and quantified.

For the optimal utilization of wind as a supplementary energy source in a system which involves hydro-electric generation], an appreciation of the joint availability of water and wind is important. Although short-term wind is not a dependable resource, its longer-term effect is a firming of energy through augmentation of storage or avoidance of reservoir withdrawals. Study of the natural wind-water time dependence in the Northwest Territories context would be appropriate to precede further wine/hydro investigations.

ÉTUDE DE LA VIABILITÉ D'UNE CENTRALE ISOLÉE D'Electricity ALIMENTÉE EN ÉNERGIE HYDRAULIQUE ET EN ÉNERGIE ÉOLIENNE DANS LES TERRITOIRES DU NORD-OUEST

Résumé

Le présent rapport porte sur la première phase d'une étude qui vise à determiner s'il est possible, en termes économiques, de répondre à des demandes de charge isolées clans les Territoires du Nerd-Ouest au moyen d'une installation de stockage d'eau pompée par énergie éolienne reliée à une centrale hydro-électrique. Le vent actionnerait aes moulins à vent ou turbines éoliennes qui pomperaient l'eau clans un réservoir plus élevé pour produire de l'électricité au besoin, grâce à des turbines hydrauliques et à des génératrices électriques. En certains endroits, une telle configuration pourrait peut-être remplacer la centrale utilisant un moteur diesel, lorsque les autres options sont moins viables.

Portée

La première phase de l'étude vise à élaborer les caractéristiques matérielles d'une installation éolienne - hydraulique autonome. Plus particulièrement, il s'agit, clans l'optique de pouvoir éventuellement en mettre une en place clans des régions septentrionales isolées:

a) de faire le bilan des nouvelles réalisations en technologies éolienne pour trouver des combinaisons prometteuses d'éoliennes, de moteurs et de pompes;

b) d'examiner des centrales hydro-électriques qui pourraient fonctionner de concert avec des éoliennes: l'acheminement d'un débit ferme vers les turbines et les génératrices hydrauliques fait forcément partie de la conception de l'installation; et

c) d'étudier, afin d'obtenir une configuration réalisable de centrale isolée, les rapports fondamentaux entre la demande d'électricité, les possibilités de la turbine éolienne, la capacité de stockage, l'élévation du réservoir et la puissance hydraulique installée en fonction d'un régime de vents et de caractéristiques de charges typiques aux Territoires du Nord-Ouest.

Résultats de l'étude

Plusieurs modèles d'éoliennes de 100 kW et plus pourraient servir dans des centrales isolées combinant l'énergie éolienne et l'énergie hydraulique. La quantité de puissance produite par les différentes unités envisagées varie selon leurs particularités conceptuelles: axe vertical ou horizontale, de construction légère, multi-pales à faible vitesse de rotation.

Cependant, cette puissance n'est pas déterminante; d'autres facteurs comme le pompage, le choix du site et l'exploitation d'une petite centrale devraient avoir plus d'importance dans la conception de l'installation. Avant de pouvoir repérer les combinaisons les plus prometteuses, il faut mieux comprendre certains de ces facteurs déterminants, soit:

a) la séparation d'éoliennes et de pompes liées mécaniquement;

b) le comportement des éoliennes à des vitesses variables, l'impulsion mécanique provenant de l'axe du rotor,

c) l'effet de la qualité de la puissance produite par la génératrice éolienne sur le réseau local, et les mesures pour améliorer cette qualité, et

d) le rendement des turbines éoliennes et des pompes dans le rude contexte nordique.

D'autres travaux de recherche et de développement et des essais sur place permettraient d'en apprendre davantage à ce sujet.

Les régimes de vent les plus favorables à proximité de collectivités isolées des Territoires du Nord-Ouest donnent des vents moyens à long terme qui se situent au bas des gammes d'exploitation des éoliennes contemporaines. Des intervalles prolongés durant lesquels les vents sont d'une vitesse moyenne considérablement inférieure aux valeurs à long terme produisent de longues périodes critiques pour la détermination de la taille des pièces de l'installation (ces périodes peuvent aller de plusieurs semaines à des mois). La puissance nominale en place d'énergie éolienne et la capacité de stockage du réservoir doivent donc être très élevées comparativement à la demande.

Conclusions et recommandations

Le manque de fiabilité du vent comme source d'énergie dans les Territoires du Nord-Ouest porte à penser que son utilisation pour produire de l'électricité dans des coins isolés serait peut-être plus rentable comme énergie d'appoint ou comme moyen d'économiser du combustible. Ainsi, dans les endroits déjà aménagés pour produire de l'hydro-électricité ou dans ceux qui pourraient l'être, on pourrait faire appel au vent ou au moteur diesel, ou encore aux deux à la fois pour remplir le réservoir, ou encore au pompage éolien pour augmenter le débit d'entrée dans le réservoir. Dans les centrales actuelles au diesel, l'énergie du vent, lorsqu'elle est produite, pourrait servir à faire baisser la consommation de combustible. Comme de l'expérience a déjà été acquise à cet égard partout au pays (y compris certains essais dans les Territoires du Nord-Ouest), on pourrait lancer des projets expérimentaux de diverses installations éoliennes dans le Nord pour étudier les aspects moins bien compris que nous avons notés ci-haut. On pourrait d'ailleurs en profiter pour étudier la possibilité d'affecter des éoliennes à l'approvisionnement en eau de collectivités éloignées.

Il faudrait aussi étudier à fond tous les moyens qui permettraient de maximiser la production unitaire d'énergie éolienne afin d'accélérer la viabilité économique des applications d'éoliennes dans le Nord. La proximité du point de consommation pourrait permettre l'exploitation d'un régime de vents anormal et localisé lorsque le potentiel estimatif de l'énergie éolienne aurait été pessimist pour la région. Des vents inhabituels à distance raisonnable des collectivités devraient être repérés et quantifies.

Pour une utilisation optimale du vent comme source d'appoint dans une installation qui fait appel à l'énergie hydraulique pour produire de l'électricité, il importe de bien évaluer la disponibilité simultanée d'eau et de vent. Même si des vents irréguliers ne sent pas fiables, ils peuvent à long terme affermir la production d'énergie en augmentant la capacité de stockage ou en évitant certains retraits au réservoir. Avant de poursuivre l'étude de l'utilisation combinée des énergies éolienne et hydraulique, il conviendrait d'en savoir davantage sur les liens de dépendance naturels entre le vent et l'eau dans le temps.

L'étude a été effectuée par Unies Consulting Engineers Ltd. pour le compte du Northwest Territories Science Advisory Board avec le concours financier d'Énergie, Mines et Resources Canada, dans le cadre de son Programme de démonstration dans les collectivités éloignées.

SECTION 1

1.0 INTRODUCTION

An uncertain future for both price and supply of oil has sparked consideration of alternative energy sources and demand reduction options since the 1970's in Canada and elsewhere. Additional impetus for this movement in Canada is provided by the price and reliability disadvantage which accompanies the importation and use of oil in communities which are isolated by geography and economics from the inexpensive forms of energy available in more populated regions. Traditionally, a combination of subsidy and restricted access to electrical supply has been used to moderate the impact of the above, but the effect of this has probably been a reinforcement of the perceived differences in opportunity and responsibility associated with residence in a remote community. The Remote Community Demonstration Program (RCDP) of the federal Department of Energy, Mines and Resources has been established with the aim to help such communities to attain greater energy self-reliance and lower long-term energy costs through exploration and demonstration of appropriate alternative supply and conservation technologies. This study, funded under RCDP, concerns itself with the reduction of dependence on imported oil in isolated communities in the Northwest Territories.

Technology for extraction of energy from water and wind has been under development for a long time, but has been subjected to shifts in interest and priorities. The demand for and utilization of electrical energy in the first three quarters of the twentieth century fostered both a dramatic increase in scale and a simultaneous refinement of technique in hydro-electric development. A majority of the larger, economically attractive hydro sites has been exploited and interest is now shifting to the more favorable of the smaller capacity developments. In order to improve cost-effectiveness at the smaller scales, advantage must be taken of standardized designs, equipment and procedures, and automated control systems.

It is only since the mid-1970's that the area of wind-energy extraction has begun to enter a comparable phase of rapid development, improving upon the familiar small-scale systems which formerly provided low-quality energy for agricultural and domestic purposes in rural locations. The industry is now about ten years into a somewhat diversified expansion-of-scale period, with research, demonstration, manufacturing, and commercialization all underway at the same time. Despite the intensity of recent effort, it is not yet clear what impact wind-energy production will have on the overall energy-supply picture.

The Northwest Territories is characterized by a sparse population which is clustered in mutually isolated centres. Oil products are consumed in the remote communities for electricity production and, in most locations, for space heating. The total of fixed and variable costs associated with these modes of energy use is dominated by delivered fuel costs. Severe climate and the inherently low efficiencies of conversion of source fuel energy to useful fores under the circumstances serve only to increase the quantity of fuel required to support a given activity in the north. The disadvantage is scarcely mitigated by a relatively low first cost for oil-burning equipment and the robust, often local, capability which has evolved for dealing with and restoring interrupted service.

The alternatives to high-unit-cost, oil-based energy normally offer modes of production which incorporate lower operating costs and a larger proportion of capital-related charges. However, the cost of construction in remote areas, including the Northwest Territories, and the unfavorable effect of scale combine to delay economic acceptability for isolated community applications. Also contributing negatively, but often underemphasized, is the disproportionate increase in cost of maintenance and repair by skilled labour when newer or unfamiliar technologies are established in remote locales.

There are, in addition, specific physical constraints to the feasibility of exploiting local energy resources. For example, even though the technology is relatively well developed, attractive combinations of flow and head for hydro-electric development tend not to be in reasonable proximity to load centres. Some communities are located in the areas of highest wind-energy potential (generally near and on Arctic and Hudson Bay coasts and islands), but the range of wind turbine capability which is available or under development may be less than ideally matched to these wind regimes aria stand-alone operation. Further, performance and reliability are yet to be proven even in more accessible environments.

The consequences of the above are clearly evident. Hydro-electric development in the Northwest Territories to date has been restricted to the more populous Great Slave Lake watershed, with several small units contributing to local thermal/hydro-electric power supply systems. Recent wind-energy extraction efforts have been more or less at the experimental level, including, for example, a wind-powered automatic weather station in the Beaufort Sea, a 3 kW system with battery storage serving a single residence, and a small unit connected to the community power supply system at Cambridge Bay.

It is possible that the various impediments to the exploitation of local water- and wind-based energy in the Northwest Territories may be circumvented with the use of some suitable combination of wind and hydraulic energy-extraction technologies. In particular, it may be advantageous to develop a site where streamflow is not adequate to support hydro-electric supply but where the physical situation would permit water to be pumped into a reservoir using wind power. The stored water could then be released through a hydro-electric generating plant to meet the electrical demand of the isolated community. The viability of an electrical supply scheme of this type is the subject of the current study.

Organized into two phases, the project first comprises an investigation of the physical nature of a wind/hydro-electric supply system in the general context of Northwest Territories applications, including the basic relationship among typical electrical loads, heads, wind regimes, and wind turbine and hydro-electric installed capacities and storage. If it is indicated that the wind/hydro concept is technically viable and practical, then the second phase of the project is to be a study of the economic viability of a wins/hydro-electric system for a selected Northwest Territories site. This report covers the first phase of the project.

Section 2 comprises a review of the wind-energy conversion subsystem, the primary consideration being the applicability of prototype and near-prototype wind turbines and pumping equipment for remote location in the Northwest Territories.

Section 3 of this report is a brief discussion of the hydraulic energy conversion subsystem in its context as part of a wind/hydro scheme.

Section 4 consists of a concept-level study of the performance of possible wind/hydro configurations. The objective sought is a general appreciation of the effects, on design, of the capabilities of current equipment in relation to the wind energy resources which are there.

Section 5 is a summary of study findings and culminates with a discussion of the implications for wind energy exploitation in the Northwest Territories.

SECTION 2

2.0 WIND-ENERGY EXTRACTION AND CONVERSION

A stand-alone wind/hydro-electric power generation system would consist of the following:

(a) a configuration of wind turbines to capture the "free" kinetic energy of the wind,

(b) drives and pumps to convert some or all of this energy to potential energy in the form of water raised to some height and suitably stored, and

(c) hydraulic turbines and generators to convert the potential energy to electricity according to the demand pattern of the community.

Each of these major components is available, with development and "refinement ongoing for common applications. Pumped-storage hydro-electric supply systems have become relatively common, but the isolated wind/hydro system requires joint operation of the wind turbine, pumping and small-scale hydro subsystems, possibly an untried combination. Remote and northern implementation necessitates additional considerations in design. In this section are reviewed the characteristics of wind-energy conversion equipment which could be adapted and combined for use in a wind/hydro-electric supply scheme. The discussion is concluded with the selection of the wind-turbine-and-pump combinations which appear to be the most workable for wind/hydro systems in the near term. These combinations are investigated further in later sections.

2.1 WIND TURBINE DESIGNS

Much has been written in conjunction with the research and development leading to today's wind turbines, and many of the possible applications of wind energy have been explored. Examples of early experience in the area of wind-energy conversion systems are provided in references (1) and (2). A cross section of issues and investigations in the field since the turning point of the mid-1970's, with emphasis on potentially promising Canadian applications, can be seen in references (3) through (14). In brief, the focus has been on units for direct electricity generation with connection to regional power grid for fuel saving, but the resurgence in wind turbine development has also included activity in the areas of small battery storage systems and water-pumping systems for agricultural applications. Development and production appears to be coalescing into the following ranges of output capacity:

(a) Small scale - from less than 5 kW up to approximately 75 kW. Units at the lower end of the range generally have been intended for rural stand-alone-with-storage (usually, battery storage) installations where central power supply is unavailable. The market focus for those at the upper end of the range has been on utility feeding applications via induction generators. This category has been characterized by higher production volumes, which has led to an accumulation of experience on performance and reliability, and on operation, maintenance and repair requirements. Installed cost is high relative to output, but the capital required per unit for purchase, and (consequently) the risk associated with its unavailability or loss, is not prohibitive. Initially the larger representatives of this group have been preferred in windfarming applications.

(b) Megawatt scale - from 1 to 4 MW or greater, for utility applications, without any direct form of storage. A very small number of prototypes are under development, and the total number constructed by the mid-1980's will be on the order of ten. Included at this scale is Canada's 4 MW Eole Project, with prototype to be erected at Cap Chat in 1985. Under mass production, and with favorable site, it is expected that the cost of energy will be relatively insensitive to capacity beyond the several megawatt size and will be significantly less than that of fossil-based electricity. However, current and prospective electricity prices are little incentive for private-sector investment in development at this time.

(c) Intermediate scale - from less than 100 kW up to 600 kW or greater, for the apparently promising windfarm market. A number of manufacturers can produce or are developing wind turbines in this category, generally as a scaling up of earlier designs, and with smaller financial requirements than those associated with category (b) above.

In general, it cannot yet be said that development has proceeaed to the stage of line production of standard models of a size which would have significant impact on regional energy supplies. Other than in the smaller scales only developmental or prototype units may now be considered to be in operation. While there are thousands of smaller units in operation in North America, the total number of larger wind turbines is only several hundred. Several catastrophic failures of larger prototypes have occurred, each being an expensive lesson. Near-future construction ana operating experience will help to resolve the major structural issues quickly, but long term durability and reliability will only be appreciated from field-scale aging.

2.1.1 Classes of Large Wind Turbines

Rotor development has received a good deal of attention in the past. The major designs now have been resolved, with remaining concerns in the areas of materials selection and quality control in manufacturing. Balance and durability in the field have become paramount considerations. Of the many designs which have been explored, three principal types may be identified in the larger capacity ranges:

(a) lightweight high-speed vertical-axis wind turbine (VAWT).

(b) lightweight high-speed horizontal-axis wind turbine (HAWT).

(c) high-solidity low-speed horizontal-axis wind turbine (multi-bladed HAWT).

The general forms of the above classes of wind turbines are indicated in Figure 2.1. For each type, a number of innovative variations of the basic form have been suggested, but only a few have reached the prototype stage in the larger scales.

The familiar relationship for wind turbine generator output power may be written as

$$P = 0.5 \rho C_p A V^3 \tag{2.1}$$

in which

P = power from wind-energy conversion system,
ρ = density of the air,
V = free stream wind velocity,
A = area swept by the rotor, and
C_p = power coefficient.

The power coefficient C_p may be further broken down as

$$C_p = \eta_{rotor} \eta_{plant} (16/27) \tag{2.2}$$

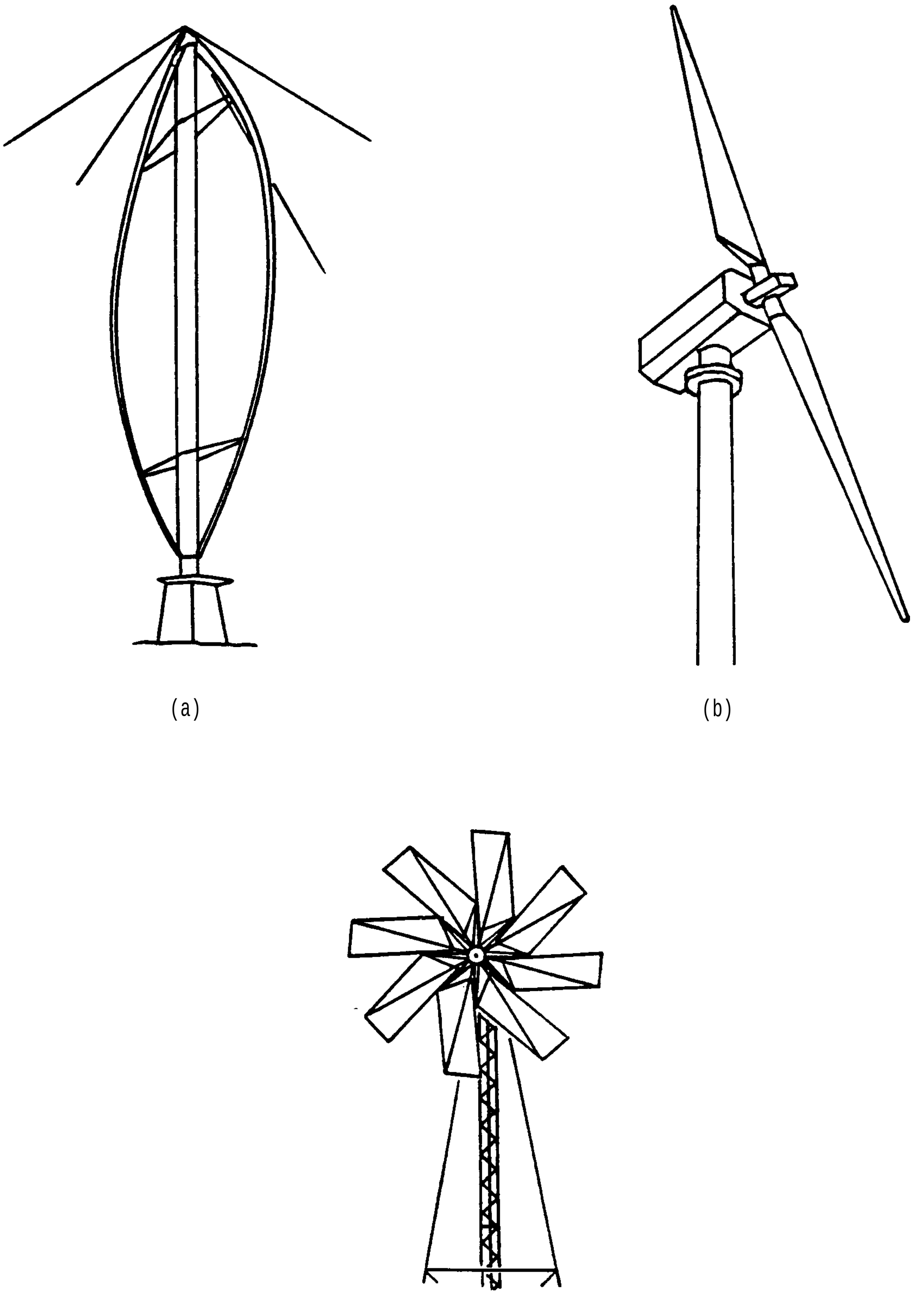
in which

η_{rotor} = extraction efficiency of turbine rotor,

η_{plant} = plant efficiency, which includes gearbox losses, generator losses, etc., according to the form of the delivered power which is derived from rotor shaft power, and

16/27 = theoretical limit of extraction of kinetic energy from the wind stream.

Rotor extraction efficiency, η_{rotor}, is a function of windspeed and rotor rpm, and varies widely, peaking at a particular combination of



(a)

(b)

(c)

FIGURE 2.1 CLASSES OF LARGE WIND TURBINES: (a) Vertical-axis, (b) Horizontal-axis, (c) Multi-bladed.

windspeed and rotor speed. Rotor designs can therefore reflect a compromise between peak efficiency and maximum energy output, because they unavoidably must be subjected to variable-speed winds.

For a given blade geometry, if the rotor can be allowed to operate at variable rpm, with suitable controls, then higher extraction efficiencies can be maintained over a wider range of windspeeds. Blade pitch angle can also be varied over a range of windspeeds effectively to broaden the range of higher extraction efficiencies. Some recent designs intended for use at constant rpm (suited for coupling to conventional alternating-current [a. c.] generators) employ variable blade geometry. Fixed-pitch blades and variable rotor rpm are used for applications with lower mechanical and electrical constraints (e.g., for direct-current [d.c.] machines or mechanical power conversion).

2.1.1.1 High-speed Rotors

Common VAWT- and HAWT-type rotors are usually low-torque aerodynamic lift devices, typically with two or three blades. Although the resumption of development of horizontal-axis designs began earlier, both types now have matured to the point of having similar peak aerodynamic efficiencies and similar potential maximum power extraction capability for the same swept area. This does not mean they should be compared on the basis of equal generator rating, however. The variable blade-pitch control of horizontal-axis designs is used to limit rotation anti output between rated and cut-out speeds. output of vertical-axis units is determined by wind and rotational speed, as the blades are fixed, and hence specific loading (power per unit of swept area) is higher for this type.

Rotors both upwind and downwind of the tower are common for larger capacity horizontal-axis turbines, and yaw control is necessary. For smaller units this function is provided by a tail vane, and for larger ones by motor-assist. Vertical-axis rotors, of course, do not have to be turned into the wind, and shaft-power extraction equipment can be mounted at ground level (at the base of the drive shaft) rather than on the tower. They are not self-starting, however, which is a significant complication for a stand-alone system (power for starting would have to be drawn from a standby or storage/generation system, for example, the hydro-electric subsystem of a wind/hydro scheme). With a higher windspeed required for starting, vertical-axis wind turbines produce less energy from light winds.

Braking systems normally employed include combinations of low-speed (rotor) shaft brakes and spoilers for fixed-geometry rotor designs, and shaft brakes and blade or blade-tip pitch alterations for designs with adjustable blade geometry. Assembly and erection at remote sites could be more difficult in the case of horizontal-axis machines because of the elevated rotor/generator.

Reliability and cost-effectiveness of power generation with VAWT- and HAWT-rotor philosophies are yet to be conclusively determined to the point where an optimum configuration can be suggested. The variety of commercially available designs is summarized in Appendix Al. In the meantime, as field experience with the mechanical aspects is being accumulated, electrical considerations associated with applications, for example, utility interfacing or diesel-assist mode, are being studied and, in some cases, demonstrated. Canada has been contributing significantly to the development and acceptance of vertical-axis rotors for these roles.

2.1.1.2 Low-speed Rotors

The multi-bladed, high-torque water pumper, on the other hand, has been built and used in North America for more than one hundred years, and longer elsewhere - a simple, sturdy and practical machine suited to unattended operation in locations not serviced with electrical power. With renewed appreciation of its value in supplying water for livestock, irrigation and people in rural areas, cost-effective rotor and drive improvements are being advanced to complement the materials and manufacturing capabilities of the country of use. Applications until recently have supported rotor diameters in the 2- to 8-metre range, but the larger-scale possibilities are now being explored. The cost and weight of the high-solidity rotors become major factors for the larger designs.

Current development and fabrication of multi-bladed, high-torque rotors with diameters in excess of 16 metres give rise to the third wind turbine type considered in this study, i.e., the multi-bladed HAWT. A single prototype erected in 1983 at Calgary, Alberta may be the first working example of its size and style.

Low and variable rotational speeds are retained in the scaled-up design, along with the good starting torque at low windspeeds, which perhaps indicates a suitability for operation in the poorer wind regimes more commonly associated with its smaller water-pumping cousins than with other contemporary large wind turbines. A tail-vane approach to yaw control has also been incorporated. Overspeed protection, through a progressive swinging of the turbine head out of the face of the air stream, is effected with a lifting counterweight which generates a processing moment. Output limiting and ultimate cut-out occur at lower windspeeds than with the lightweight rotor designs, in order to limit tower stresses and therefore reduce structural requirements.

2.1.2 Drives for Wind Turbine Power Delivery

2.1.2.1 Drive Alternatives for VAWT and HAWT Rotors

Usable power is extracted from the wind turbine rotor shaft of intermediate- to large-capacity units in either electrical or mechanical form. Conventionally, the lightweight airfoil designs are operated at constant rotational speed with power transmitted via speed-increasing gearing to alternating-current generators. Both synchronous and induction generators can be and are being used for utility applications, but synchronization of the former can be difficult to achieve under unsteady input windpower conditions, and the latter conventionally draws excitation voltage-ampere from the grid and requires power factor correction. The non-self-starting vertical-axis turbines must in addition be provided with auxiliary starting motors. Unsteady rotor shaft power input caused by gusts and cyclical rotor torque variations also necessitates increased attention to generator output voltage and frequency. Output quality is one of the major factors which currently limits the penetration potential of wind turbine generators in utility applications.

Static power converters are relatively efficient and reliable power electronics equipment using semi-conductor switching for conversion of electric power from one form to another, i.e., d.c. to a.c., a.c. to d.c., d.c. to d.c., or a.c. to a.c. They can be used to advantage between the wind turbine generator and the power grid as control devices (15). For constant and quasi-constant rotational speed wind turbines with synchronous generators, use of a symmetrical d.c. link converter (rectifier-inverter) to deliver a static frequency to the power lines could reduce significantly the undesirable effects of unsteady winds. Disadvantages include a high cost, by-product harmonics injected into the power lines, and a requirement for reactive power supply.

Other proposals have been made for incorporation of static power converters with constant-speed induction-type wind generators, and for variable-speed wind turbine generators in stand-alone or grid-connected applications. Experimental work with the above control systems applied to windpower exploitation is extremely limited at this time. It would appear, therefore, that early viability of stand-alone electricity supply schemes with a.c. power generation from the wind as the primary component may be dependent on further development in the area of power electronics.

Experimentation with other drive configurations has been sporadic. The electricity-generating, horizontal-axis wind turbines have conventionally been designed with gearbox and generator mounted in close proximity to the rotor shaft, i.e., at tower height. Gear-and-shaft drive trains with generator located on the ground have been used for d.c. or a.c. power production with or without storage, with generator ratings up to about 25 kW. This activity occurred primarily before the current resurgence in interest in windpower. Loss of interest in the concept at the time was caused by the growing availability of less expensive fossil-based power. Little renewed development has occurred in this area.

In the 1950's, a 100 kW wind generator was built in England with a main horizontal-axis rotor and a second vertical-axis air turbine (and attached generator) located in the tower base. The latter was driven by an air stream drawn up the hollow tower by the main rotor which had hollow blades with openings near the blade tips. The efficiency of this unit was found to be low in comparison to other designs.

A mechanical coupling of an early 10 kW vertical-axis wind turbine to a 12 kW diesel-electric generating set at Toronto Island Airport in the later 1970's proved to save more fuel than when an electrical coupling was used (more losses through generator, etc.), and led to trials with a larger wind/diesel hybrid at Sudbury (6). The initial configuration tested there, from early 1982, was a 30 kW vertical-axis unit geared up and mechanically coupled to the shaft of the primary of two 50 kW alternators, each of these being driven by a 46 kW diesel. In such a setup, windpower input is treated as a negative load by the primary diesel with output stability effected by the diesel governor, and with the excess of production over demand dissipated via dump load resistor banks.

Experiments were begun in 1983 to evaluate wind/diesel operation further with mechanical and electrical coupling and with wind turbine in stand-alone mode using a synchronous generator and dump load frequency control. For retrofit situations the electrically coupled wind/diesel configuration may be more practical from the standpoint of optimal siting of the wind turbine and in terms of simplicity of construction. In general, however, mechanical coupling of VAWT-type rotors for a variety of other applications would appear to be an area holding much promise because of the availability of shaft power at ground level.

2.1.2.2 Drive for Multi-bladed HAWT Rotors

The low rotational speeds of the traditional large-bladed windmill are converted mechanically to reciprocating or rotational motion, retaining the low speeds. For the 16-metre (and larger) rotor sizes, the initial approach has been again to convert to reciprocating motion but with innovations to improve system efficiency over the range of windspeeds encountered. In order to balance loads more uniformly over the entire rotational cycle, a double-acting take-off has been incorporated with operation 180 degrees out of phase. In addition, simple hydraulic control of stroke length is used to vary the load seen by the rotor, and hence, through control of rotational speeds, to maintain a higher wind-energy extraction efficiency throughout the operating range.

2.1.2.3 Drives for Wind/Hydro Systems

Experience with alternative drive arrangements is clearly limited at this time. Commercial activity is concentrated, for the larger lightweight vertical and horizontal-axis wind turbines, on the simple delivery of a.c. electrical power via gearbox and generator. Experimentation with other configurations, as described above, has so far been limited to smaller scales. Similarly, the more recent scaling up of low-speed horizontal-axis designs has included incorporation of a familiar drive system, i.e., simple reciprocating motion.

Because of the levels of development and the related levels of interest shown for the above prototype-stage drives as compared to other possibilities, it is reasonable to consider only the former for wind/hydro combinations in the near future. Thus, for VAWT- and HAWT-type rotors, the most practical drive system for contemplated applications would be that of the familiar speed-increasing gearing and a.c. generator. For the low-speed multi-bladed HAWT type rotor, conversion of rotor shaft power to reciprocating motion would appear to be the most usable drive mechanism for the near term.

2.2 WIND-DRIVEN PUMPS

Both centrifugal and volumetric pumps may be considered for the problem of lifting water from low-level source to high-level storage basin.

2.2.1 Centrifugal Pumps

Performance of centrifugal pumps is determined as a function of the following interdependent parameters: (a) flowrate or capacity, O, (b) the increase in energy content of fluid pumped, usually expressed in terms of head, H, (c) input power, P, (d) efficiency, η, and (e) rotational speed, N. For standard production units, the interrelationships among the above are not subject to modification. For a particular pump, the higher efficiencies are obtained over a relatively small combined range of the other parameters. Thus it would be appropriate to start with a site-defined pumping head, along with the wind turbine output power available as pump input power (i.e., at any particular windspeed and rotor rotational speed) and to identify standard pumps which operate at suitable rotational speeds and at favorable efficiencies under those conditions.

Through investigation of the pump possibilities for the full ranges of wind and rotor speeds, a suitable gear ratio for mechanical linkage of wind turbine to pump can be selected. Wind turbines can be allowed to turn at variable speeds with this mode of operation, but it should be remembered that centrifugal pumps would be running at varying efficiency over the operating range of windspeeds. Start-up and high-limit control requirements and philosophies for wind-turbine-and-pump combinations would have to be resolved. The most serious difficulty with a mechanical linkage of this type would be the likelihood that a favorable site for wind turbines would not be close to a good location for the pumps.

An electrical linkage between wind turbines and a group of centrifugal pumps operated in parallel would appear to be a more logical approach at this time, because of the associated siting flexibility and because of the use of equipment which is readily available. Each pump would be motor-driven at constant speed at a favorable point in its operating range. The number of pumps on-line at any time would be programmed to match available power from the wind turbine generators.

The nature of the generator output would still be an important consideration with this approach. Pump motors in an electrically linked configuration generally would require a similar quality of electrical supply as other common loads, but some electrical equipment likely to be in use in a community would have stricter tolerances. Experience with variable-speed drives and electronic controls to smooth cyclic or wind-gust-induced fluctuations, as indicated in Section 2.1.2.1, is quite limited for wind turbine generator applications, and considerable development is necessary in this area. A result of successful voltage- and frequency-control technology, of course, may be a freedom to generate directly to community load from the wind turbines standing alone and to pump water to storage using any excess power. There may be other advantageous operational schemes made possible.

A project of the Nova Scotia Power Corporation to evaluate a full-scale electrically connected pumping scheme began in 1980 at Wreck Cove Reservoir, using a 200 kW horizontal-axis wind generator. Both the unit's present induction generator (1984) and the 200 MW hydro plant are grid-connected, the latter operated only for late afternoon system peaking. The pumping is in the form of an interbasin transfer of water. Outages have been extensive, however.

For both the high-speed vertical-axis and horizontal-axis wind turbine types, the motor-driven pump scenario appears to hold the most promise. The suggestion of the most appropriate formats for wind/hydro implementation realistically is dependent upon the progress of control system innovation, however. Initial field installations of advanced electrical equipment would most advisably be in settings easily accessed by qualified personnel.

2.2.2 Volumetric Pumps

Use of reciprocating pumps is a natural choice for low-speed wind turbines. For smaller windmills, the principle has been successfully used for a long time. Delivery rate for a reciprocating pump depends only on its piston speed. High lifts are possible if the piston cylinder is positioned close to or below the water line of the low-level source. Efficiency is potentially very high, but, as most of the losses are attributable to slippage, it depends critically on the condition of the valves and seals.

The increased concentration of power capture at the rotor shaft for larger units allows the utilization of pumps of large displacement. For example, the 16-metre prototype in Calgary incorporates two pumps each with cylinder diameter of approximately 1.3 metres and with maximum stroke length of approximately 1.2 metres. The operation of the two pumps is 180 degrees out of phase to smooth load fluctuations over each pumping cycle. Piston travel is automatically shortened at lower windspeeds and lengthened at higher windspeeds as a means of load control to extend the range of highest-efficiency windmill operation. Conversion efficiency, from power at the shaft to pumped flow, observed during prototype testing in 1984 was approximately 75 percent (16).

Finally, for the large-scale reciprocating pump, there remains the significant problem of finding a site which is viable in terms of its potential for capture of wind energy as well as in terms of its proximity to the source of water to be pumped. The problem is, of course, common to all mechanical linkage schemes. The Calgary prototype’s pumps are separated horizontally from the wind turbine tower, power being transmitted mechanically via rigid linkage. The latter could be adapted for many sites requiring moderate separation of wind turbines and pumps. For greater separation of wind turbine and pumps, or for difficult topography, a continuous-loop, steel-cable drive has been proposed, but not yet demonstrated. Its development could be a necessary prerequisite for the electrical supply scheme investigated herein, because of the extended flexibility for siting it could allow.

2.3 WIND-TURBINE-AND-PUMP COMBINATIONS FOR WIND/HYDRO STUDIES

Windpower technology is, as reviewed above, still in the pre-production stage. The need for further technical refinement is primarily due to the nature of the energy resource being tapped - the power of the wind is dispersed, variable, and its availability on a short horizon is unpredictable. Thus, for wind to form a non-negligible part of the energy supply picture, there is a requirement for large wind energy conversion devices. Physically this means structural frames and large energy-capturing rotors which must satisfactorily endure the highly non-uniform stresses provided over the rotor swept area by the passing air stream. Controls to maintain acceptable output quality in the face of complex temporal variations in rotor shaft power are also necessary. In contrast, the more conventional stockpiling of fossil fuels and water at the point of use today allows controlled energy conversion into delivered forms under steady-state or only slowly varying conditions.

Although structural durability and output control techniques continue to be refined, a reasonably clear definition of the expected product can now be composed. For a wind/hydro application in a remote community in the Northwest Territories, and with community peak electrical power demand under 1 MW, the intermediate and large categories of wind turbines can be viewed as practical options. Megawatt-scale units properly may be dropped from consideration until much more operating experience with them has been accumulated. As indicated, only a handful of prototypes has been constructed. The redundancy requirements of a stand-alone system would also suggest that several wind turbines of intermediate size should be preferred over a single large unit.

Choice of wins turbine type would appear to be less of a major concern at this time than, for example, drive configuration. A relatively small group of organizations and corporations is involved in development and commercialization of wind turbines in the 100+ kW range. Descriptions of available models are attached in Appendix A. Due to rapid development ongoing in the industry, the information should be considered as indicative only, and subject to change.

For some vertical- and horizontal-axis wind turbines, examples of performance are given in Figure 2.2. All units are outfitted for utility interconnection and comprise integrated rotor/generator sets (12). Output is shown in the figure for windspeeds at rotor hub or equator height, and may be considered to be representative for recent lightweight wind turbine designs in the intermediate and larger sizes. Variations in output curves at the high ends of the operating ranges reflect generator sizing and operation of the fixed and variable pitch approaches into the stall regime.

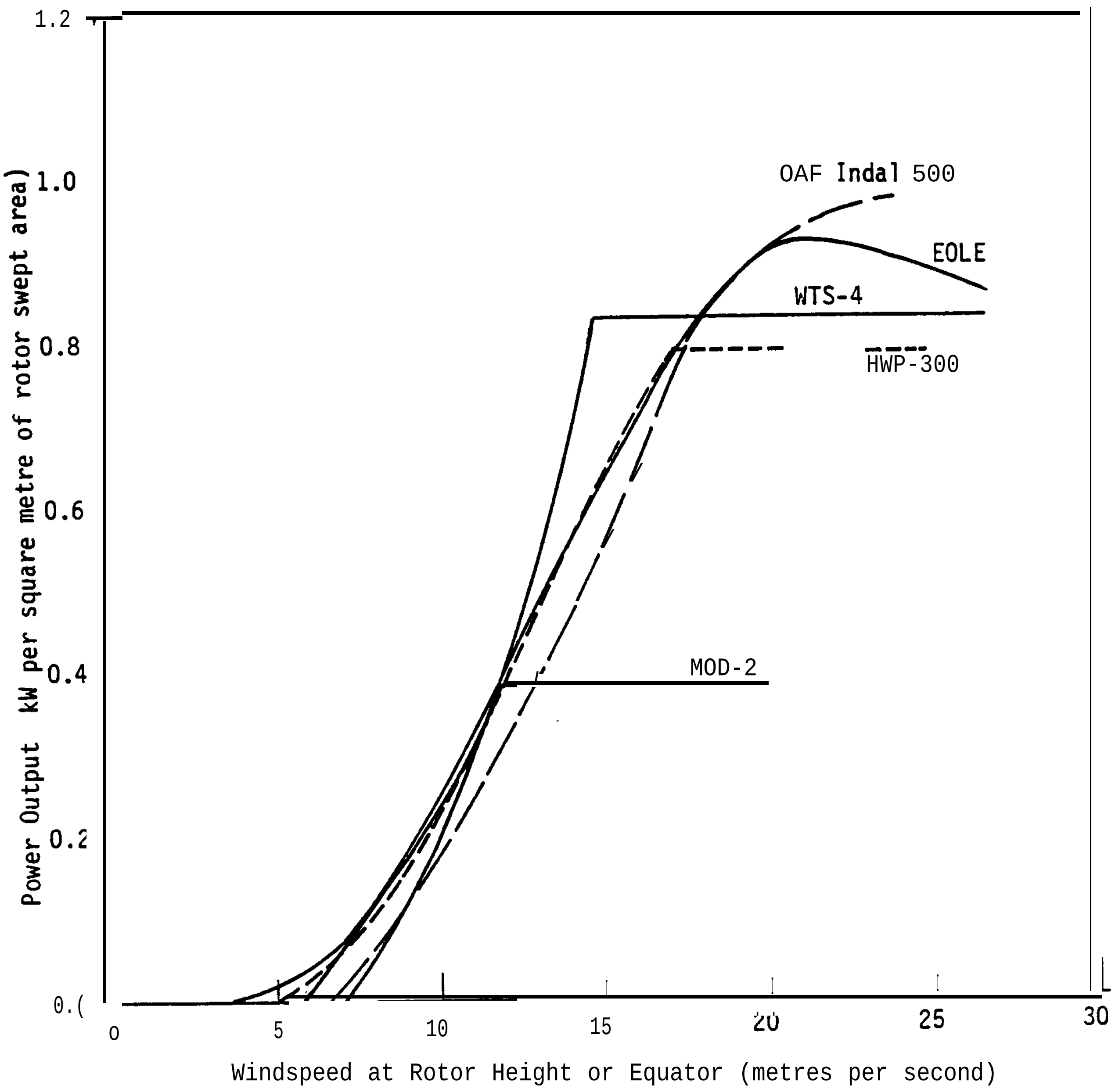


FIGURE 2.2 POWER CURVES FOR VARIOUS INTERMEDIATE- AND MEGAWATT-SCALE WIND TURBINE GENERATORS

At an average site, some advantage could be associated with the larger wind turbines which would be exposed to somewhat higher windspeeds because of their greater elevation above the ground. The relevant boundary layer function is given as

$$\frac{V}{V_o} = \left(\frac{h}{h_o}\right)^{\alpha} \qquad (2.3)$$

in which wind velocity V at elevation h may be related to velocity V. at reference elevation h_o through wind shear exponent α. The latter is dependent upon site conditions with, for example, values of 0.14 to 0.17 being generally accepted as representative of open, rolling terrain.

Characteristics of the water-pumping 200 kW Deltx WP65 (described in Appendix A), as an example of the multi-bladed type of wind turbine, are shown in Figure 2.3 in comparison with the wind regime at Baker Lake. The characteristics of the 500 kW DAF Indal Series 6400 vertical-axis wind turbine and the 300 kW Howden HWP-300 horizontal-axis unit are also included. Prototypes of each have been operatea successfully in freezing temperatures and thus they may be viewed as being potentially suitable for use in a northern wind/hydro scheme. However, overall wind turbine suitability for the application cannot be inferred from the figure, the projected output being only one of the determining factors. Others would include expected service life, reliability and costs, for example.

A simple electrically coupled pumping mode is assumed in Figure 2.3 for the VAWT and HAWT examples, with efficiency of conversion of wind

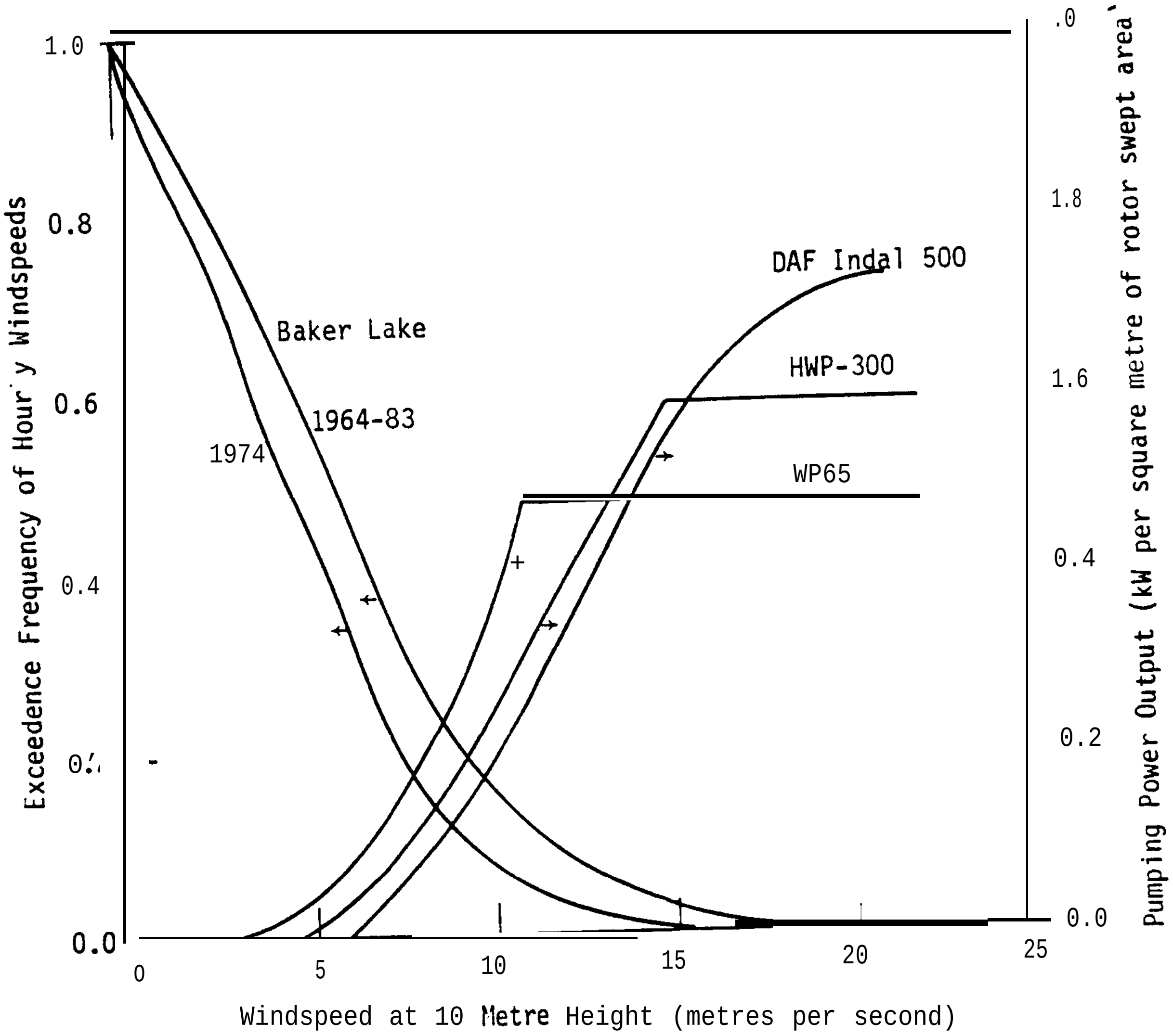


FIGURE 2.3 PUMPING POWER COMPARISON FOR VARIOUS WIND TURBINES (α=0.16; explanation in text)

turbine generator output to pumped flow set at 75 percent over the entire range of windspeeds. The pooled electrical power output of a group of wind generators is considered to be provided to an adjacent set of large (100+ kW) motor-driven (at constant speed) centrifugal pumps, the number engaged at any time being a function of available windpower (this mode of operation is discussed further in Section 4.5.2). The value of 75 percent applied in the figure to the multi-bladed HAWT example refers to conversion efficiency from rotor shaft to pumped flow via mechanical linkage.

Because each has a different rotor elevation, the three wind turbines shown in Figure 2.3 are compared in a common wind regime with wind shear exponent a set to 0.16. Windspeeds are reported at a reference elevation of 10 metres, standard anemometer height. With a hub height of 31.7 metres, the WP65 is exposed, on the average, to a wind regime with higher kinetic energy content per unit swept area than are the other two wind turbines (rotor equator height for DAF Indal Series 6400 is 21.3 metres; hub height for HWP-300 is 22 metres).

In light of the low kinetic energy density in low winds, and respecting the uncertainty which is in the performance projectiles, it can be seen from Figures 2.2 and 2.3 that the differences among the three wind turbine types near the lower ends of their operating ranges are not major. To put this in perspective, reference is made to the annual wind energy profiles shown in the Northwest Territories Science Advisory Board Report entitled <u>Wind Energy in the Northwest Territories</u> (17).

At a relatively poor windpower location, Yellowknife, windspeeds are shown to have exceeded 11.1 m/s (40 km/h) less than one percent of the time in the 10 year period 1967-76. At Sachs Harbour, a better location, 11.1 m/s was exceeded approximately 4 percent of the time. At Baker Lake and Cambridge Bay, which are representative of communities with the most favorable wind regimes in the Northwest Territories, the windspeeds exceeded 11.1 m/s approximately 8 percent and 11 percent of the time, respectively.

There may be particular sites near these communities where enhancement of average windspeeds is effected by the local topography, but at the sites for which wind records are available, operation would be below optimum ranges, particularly in the poorer years. The average windspeeds at the best of these stations are in the same range as the cut-in windspeeds of the various wind turbines. In an extended period of low winds some additional energy could be captured with a lower cut-in speed.

For Baker Lake, superposition of wind turbine power curves on the monthly wind frequency distributions [based on 20 years (1964-1983) of hourly windspeeds and temperatures and long-term mean monthly barometric pressures (the latter two are used for air density correction)] results in the projected average power outputs shown in Table 2.1 ($a = 0.16$).

Where energy must be dependable (making use of suitable storage), average output over shorter periods becomes important. The year 1974 is the worst calendar year for wind at Baker Lake. Sequences of consecutive months in 1974 (e.g., Table 2.1), as well as in other years, exhibit average wind-energy availability significantly below long-term values. The severity of temporary wind-energy shortages is further enhanced when the episode of favorable winds which follows a relatively calm period is

TABLE 2.1

ESTIMATED AVERAGE WIND TURBINE PERFORMANCE AT BAKER LAKE

Wind Turbine Model		Howden* HWP-300	DAF Indal* 6400-500	Deltx** WP65
Nominal Output Capacity (kW)		300	500	200
(kW/m^2)		0.789	0.840	0.649
Interval	Av. Windspeed (m/s)	Average Power (kW/m^2)		
Jan 64 - Dec 83	5.87	0.169	0.134	0.208
Jan 74 - Dec 74	4.66	0.104	0.075	0.141
Apr 74 - Sep 74	4.27	0.062	0.038	0.096
Jul 74 - Aug 74	3.60	0.021	0.008	0.044

* Generator output power.
** Shaft power.

interrupted by another extended period of withdrawal from storage. The energy delivered to storage in an interval falls rapidly as average windspeed decreases, because of proximity to wind turbine cut-in speed.

It would be preferable, in light of the above, to seek sites where wind is locally accelerated in order to increase energy capture in the critical intervals, but economic considerations would limit the justifiable length of transmission line from the site to the community. Until such sites can be identified and their wind regimes quantified, the wind energy records which have been accumulated may be taken to be generally representative of the wind characteristics for eligible wind/hydro sites. For certain stations in the Northwest Territories, however, it is recognized that the instrument position has tended to bias the resulting wind data (17).

Cost, not so far considered, and other factors related to the workability of pumping schemes using mechanical or electrical energy may be expected to have a greater effect on the determination of the most suitable wind turbine type and model than is wind-energy conversion capability. Much depends on the directions taken by the industry. The little activity in the wind-powered pumping area which has occurred has included the development of one intermediate-scale wind turbine expressly for the pumping of water. Most interest in windpower, however, has been focussed on the generation of electrical power directly, without storage.

Isolation-related factors would be common to all windpower installations in the Northwest Territories. New technologies are subject to teething problems which would he difficult to monitor and correct at a remote site. The potentially greatest differential impact, however, would be that resulting from operation in the severe northern climate. Although prototypes have functioned at low temperatures and under icing conditions, experience is too limited with each product to have provided an indication of what to expect in the north. It thus would be advisable to consider wind turbine installations in the near future in the Northwest Territories to be experimental only. Demonstration should be restricted to scales and applications that have been proven first in a temperate environment.

In light of the discussion in this section, several wind-turbine-and-pump combinations are considered for the investigation which follows:

(a) Decoupled mode (hydro-electric subsystem meets community load):
    (i) Multi-bladed low-speed wind turbine with mechanical linkage to volumetric pumps, or
    (ii) VAWT- or HAWT-type high-speed wind turbine/generator with motor-driven centrifugal pumps.

(b) Direct generation mode (hydro-electric subsystem meets shortfall between available wind-generated power and community demand):
  (i) VAWT- or HAWT-type high-speed wind turbine/generator with motor-driven centrifugal pumps.

The multi-bladed wind turbine delivering mechanical energy is attractive because of simplicity and the capability for energy production in low winds. Wind-electric generation, on the other hand, offers power in an inherently convenient form. Suitability of a site would be determined, before all else, by which of the above approaches could be implemented. As has been indicated, workability of each combination may be critically dependent on further developments in drive systems and/or electrical control systems. In later sections of this report, it is assumed that these developments would be made, and the overall viability of the wind/hydro concept is investigated.

SECTION 3

3.0 HYDRO-ELECTRIC SUBSYSTEM

In contrast to the wind-energy extraction component, the conversion of hydraulic energy to electrical energy as part of a wind/hydro-electric supply system would constitute an adaptation of a refined technology. Mechanical and electrical equipment performance, reliability, and cost are all well known. Civil features and the nature of the impoundment are highly site-dependent, but methodologies for assessment and design have matured. There would be only a few peculiarities of the proposed application which would have to be addressed.

Recent focus on smaller hydro-electric developments and retrofit applications has been accompanied by interest in cost reduction via standardization. To date major advances have been made by the manufacturers of hydraulic turbines and generators in offering lines of pre-designed packages in the 100+ kilowatt to several megawatt range. The process of specification of a turbine to meet the requirements of a mini-hydro scheme may now be replaced by the selection of the best available machine. For small developments with individual units under about 500 kW, the cost saving is considered to be worth the loss in efficiency compared to a custom design.

The other two major cost components besides equipment, i.e., civil/construction and project design/management are less amenable to standardization. Civil engineering works are highly site-specific and less dependent on construction materials and methods. In general, total civil and engineering design costs are disproportionately higher for small hydro developments than for traditional projects. Several manuals (e.g., 18,19) have been compiled recently, however, to make it easier to design and estimate the cost of small hydro-electric power plants.

Although having many conventional aspects, an isolated wind/hydro system would be unusual as a small-hydro development alone. In context, mini-hydro plants are rarely other than the run-of-river type, with minimal storage. Advantage is taken of available concentrations of head, while the cost of reservoir development usually cannot be justified. Most of the mini-hydro sites under consideration by utilities in Canada would be interconnected with a central grid and would be new developments rather than adaptations of existing dam sites (18).

In comparison, a wind/hydro-electric supply system for a remote community in the Northwest Territories would require a new storage reservoir of size which depends greatly on the trade-off between its cost and that of the wind-pumping system - both are highly dependent on site conditions (the local topography and wind regime). It should be noted that there is a potential for more wind/hydro sites within the vicinity of a community than pure hydro sites. This comes about because a natural flow of water is not a necessity. However, a low-level source of water to be pumped must be found near a developable head.

3.1 HYDRO-ELECTRIC GENERATING EQUIPMENT

Mechanical and electrical components for small hydro-electric generating plants are available for any head which would be considered in a wind/hydro scheme in the Northwest Territories. Flow, the other major variable, would be provided, by definition, through sufficient wind-pumping capacity as requirea by the demand for electrical energy. Selection of installed capacity therefore would depend upon load characteristics (load shape and future energy requirements), costs and hydro subsystem reliability. Firm capacity for the isolated system would likely be defined as installed hydro capacity less largest unit rating under minimum head conditions.

The choice among impulse (e.g., Pelton, Turgo), reaction-radial (e.g., Francis), reaction-axial (e.g., Propellor, Kaplan), and cross flow (e.g., Ossberger), as the major types of turbine/generator sets, has become classical and is site-dependent. For the head range of approximately 10 to 150 metres which would probably cover most Northwest Territories applications, all but impulse turbines could find application. Generators for the isolated electrical supply system would necessarily be synchronous. Figures 3.1 and 3.2 indicate the general characteristics of candidate systems, and are adapted from reference (18). Manufacturers Of small hydro-electric units are listed in many publications (e.g., 19). For exploratory work, a combined hydro-electric plant efficiency of 80 percent can be used, assuming approximately 88 percent for turbine, 97 percent for geared coupling, and 93 percent for generator/transformer.

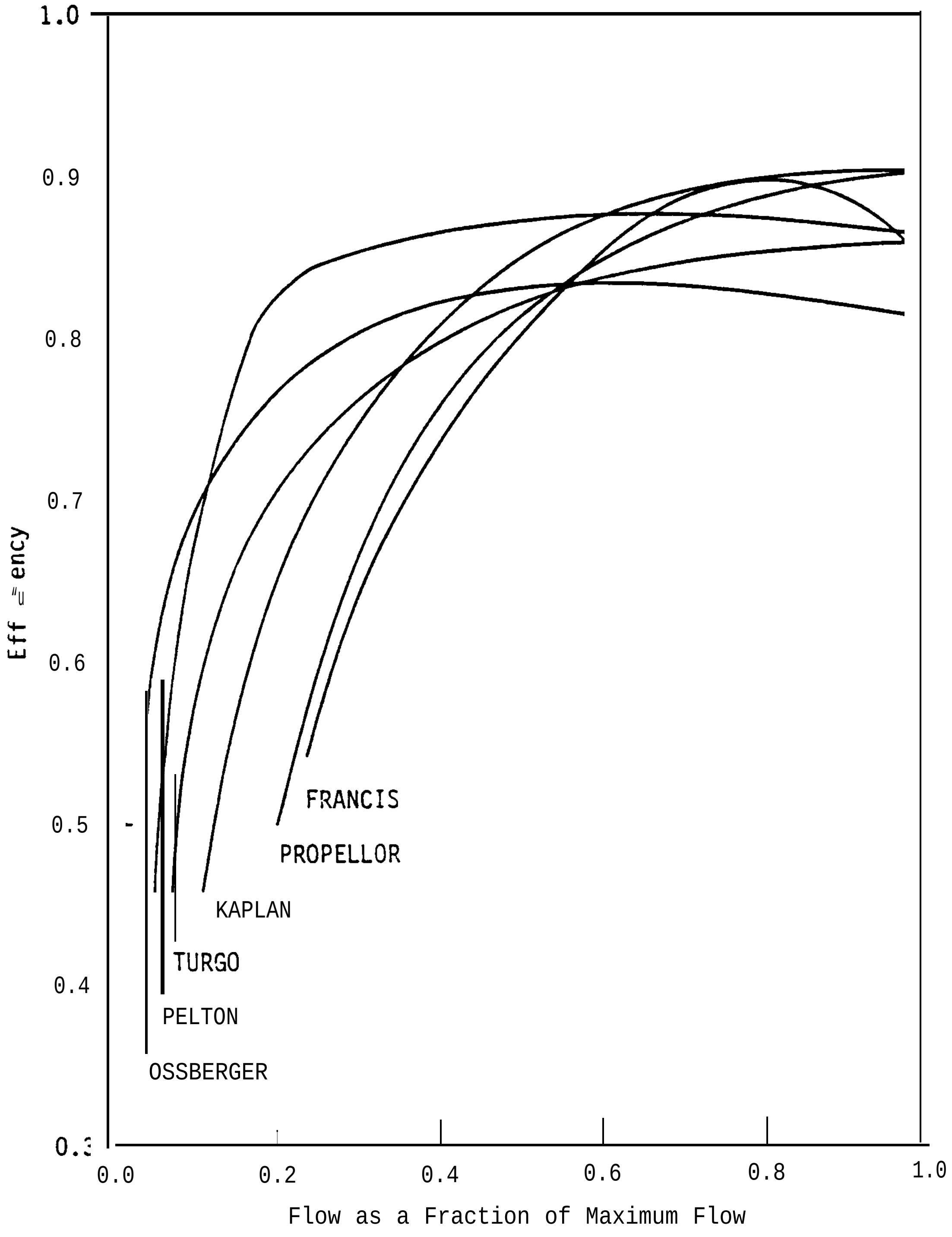


FIGURE 3.1 TYPICAL PERFORMANCE OF HYDRAULIC TURBINES

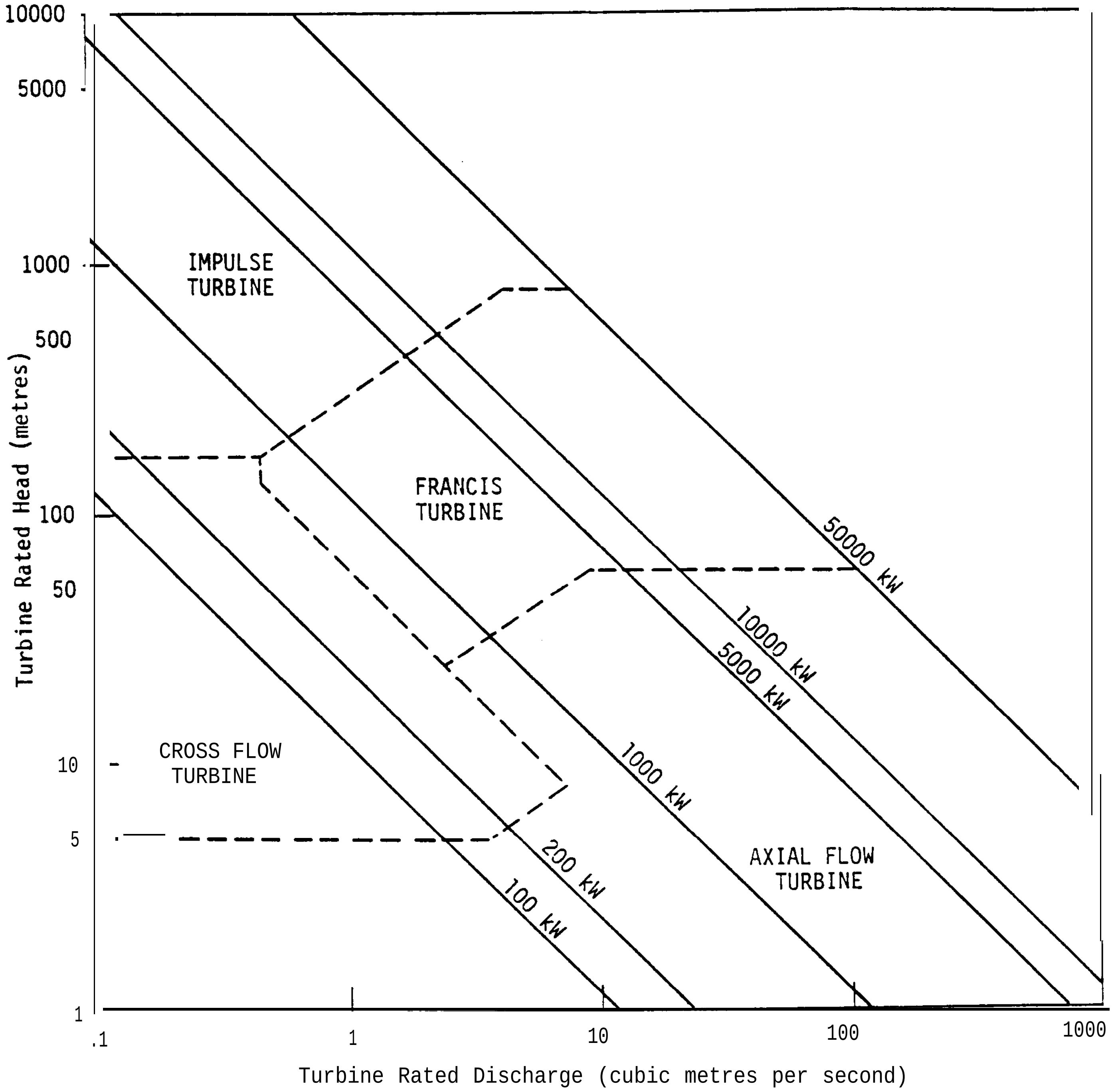


FIGURE 3.2 APPROXIMATE RANGES OF APPLICATION FOR SMALL TURBINES

Interest in the use of common centrifugal pumps as turbines in small scale installations has also been increasing due to the cost advantage. The number of applications to date is limited, but reported performance has been satisfactory (20).

The selection of hydro-electric generating equipment for a wind/hydro system would not be significantly different from that for a conventional small hydro scheme, if a decoupled pumping configuration were specified, i.e. wind turbines not interconnected with the hydro-electric supply system. This corresponds to wind-turbine-and-pump combination (a) of Section 2.3, except for wind turbine/generator models requiring system support. However, any proposed electrical interconnection of wind turbines and hydro-electric supply system would necessitate consideration of the consequences for the supply system, including control and protection issues. For the purposes of the current study of the general nature of a wind/hydro system it is assumed that these equipment problems would be solved.

3.2 HYDRAULIC DELIVERY SYSTEM AND RESERVOIR CONSIDERATIONS

The positioning of upper and lower reservoirs, wind turbines and pumps, and dam and powerhouse all depend on topography and wind regimes. Constraining the above is the requirement for piping from low-level reservoir to upper storage reservoir and the locating of the pumps probably close to the low-level intakes (if feasible, the flexibility of a motor-driven pumping scheme with remotely sited wind turbines would be clearly an asset). There is also the requirement for low- and high-pressure conduit from the storage reservoir to the powerhouse, along with intake, surge tank, and tailrace.

In the general case, the two hydraulic delivery systems would be separated. At a good site it may be possible to merge the two conduits. In that situation, head at the turbines would be maintained by the level of the upper reservoir, but the driving f"low could be supplied from the reservoir and/or directly from pumping (schematic is shown later as Figure 4.1). However, the optimum configurateion could only be suggested from a thorough site investigation.

The functioning of the hydro-electric generating plant and wind-powered pumping system in the Northwest Territories would include months of operation at air temperatures below the freezing point of water. A good deal of winter operating experience has been accumulated under conditions similar to those expected for this application. Two critical design considerations may be noted, however. Each may affect the choice of site.

Ice cover can restrict the full use of reservoir storage capacity for a hydro-electric plant. For a small run-of-the-river system, relatively steady flow is generally maintained under a stable cap of ice. With a typical occurrence being several consecutive days (or more) of light winds at a site, the storage for a stand-alone wins/hydro system clearly must be sufficient to withstand prolonged periods of drawdown. Replenishment over similar time scales must also be tolerated. Depending on the nature of the reservoir, this could mean ongoing fracturing, flooding, and refreezing, which could progressively decrease usable storage, and possibly endanger intakes, etc. The low-level basin could be affected similarly.

The second related consideration has to do with the hydraulic delivery systems. In the simple case where the community load is supplied from the hydro-electric generating station alone, flow through intake and penstock is continuous. The delivery of water to storage by wind-powered pumps is intermittent, however, due to the nature of the energy source. Periods of no flow could be long enough to allow freezing of water in the conduits. Means of protection could include drainback systems, combined hydraulic delivery systems, burial and/or insulation of pipelines, or heating systems.

The various options require study and, again, site considerations may or may not dictate a reasonable solution. Sufficient cover may not be available at sites in the Northwest Territories to allow burial of pipelines. If a combined water distribution network is used to sustain water movements during periods of no pumping, adequate precautions against shock loads in the conduits and at the turbines would have to be included. It may be reasonable to conclude that energy requirements for frost protection could be provided with additional wind-energy conversion capacity, if cost-effective.

3.3 FEASIBILITY

The wind/hydro-electric supply system is essentially a small hydro-electric head-development scheme with flow provided to the site by wind energy. A storage reservoir is used to control the effect of the unreliability of the wind as an energy source. The system is proposed as a supply alternative to expensive diesel-generated electricity in remote northern communities, in cases where conventional alternatives, e.g., mini-hydro, are uneconomic or unworkable.

By its nature a combination of developing and refined technologies, the wind/hydro system will be high in capital cost, but promises low operating costs. Component technical viability depends on additional developments to allow linkage of wind turbines, pumps, and hydro plant in an isolated system. It has been shown that wind turbine technology is in a state of flux and should preferably have its innovations proven near the factory before the added stresses of implementation in the north are imposed. The problem of handling water in sub-freezing temperatures can probably be dealt with as a matter of course.

On the assumption that the required breakthroughs in hardware development can be made, the latter part of this report comprises an examination of the expected physical performance of wind/hydro schemes.

SECTION 4

4.0 WIND/HYDRO SYSTEM SIMULATION

4.1 ROLE OF SIMULATION IN WIND/HYDRO INVESTIGATION

Screening of wind energy conversion system alternatives (sites, equipment) is normally and sufficiently limited to analysis of long term energy production using wind frequency distributions. For ungauged sites a standard Weibull/Rayleigh distribution is usually assumed. The principal feature of systems suitable for analysis in this way is the lack of a requirement for storage. Thus, the high profile to date of the average-annual-energy approach is due to the predominant interest in grid-connected wind power systems.

Storage of diesel fuel is used in conventional isolated diesel-electric generation systems to allow for uncertain deliveries. In northern Canada, at-site storage capacity is commonly greater than one year's supply. Storage of water as potential energy is used in conventional hydro-electric supply systems as a means to adjust for the vagaries of streamflow. Depending on the topographical situation, the installed capacity, and the eventual role to be assigned to the hydro plant by the utility in accommodating the overall system demand pattern, the development of the required storage reservoir can be a major constituent of the total project cost. Optimal sizing therefore is important.

Maximum storage requirements may be determined through imposition of hypothetical or planned reservoir withdrawal schedules upon the actual or inferred upstream hydrologic system, i.e., the familiar mass curve approach. The uses for mathematical system simulation have been extended beyond this to include investigation of other design parameters, evaluation and optimization of schemes for operation, and adoption of mathematical models as forecast/planning tools for decision-making in real time.

The erratic natural resource to be allowed for and adapted to in the wind/hydro-electric supply system operation is the wind. Wind-derived power provides the water for use when needed, and its unreliability determines the requirement for storage. Therefore, it is necessary and appropriate for design purposes to simulate operation of the wind/hydro system. At this concept stage the simulation would be most used as a tool for the screening of alternative system configurations. However, with the suggestion of an acceptable system format, simulation would be immediately employable for preliminary sizing of components prior to and for feasibility-level assessments.

Wind/hydro system simulation routines have been prepared as a part of this project to aid in the investigation of the viability of a stand-alone installation for Northwest Territories applications. Specifically, the relationships among typical electrical loads and wind regimes of the Northwest Territories and the sizes of the several major system components are examined.

4.2 REPRESENTATION OF WIND/HYDRO SYSTEM COMPONENTS

A schematic of important system elements is shown in Figure 4.1. As has been indicated in earlier sections, the prototype can be conceptualized

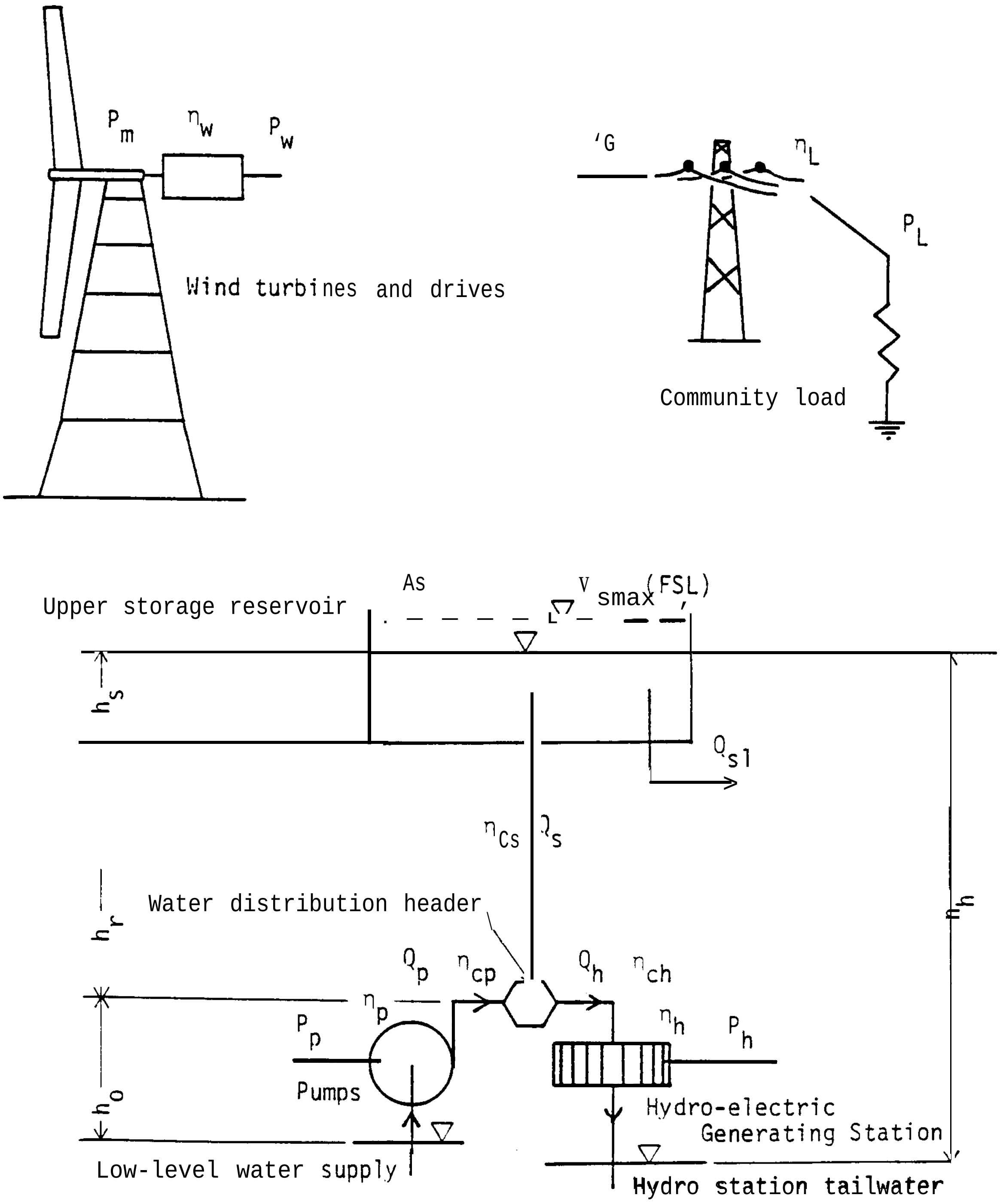


FIGURE 4.1 MAJOR WIND/HYDRO SYSTEM COMPONENTS

as a novel interconnection of developed and developing components, with various electrical and mechanical arrangements possible. The essential parameters may be summarized as follows:

(a) Upper Storage Reservoir

A_s = surface area of reservoir

V_{smax} = reservoir volume

h_s = depth of water above reservoir datum

h_o = elevation of water supply distribution header relative to water level of lower supply basin

h_r = elevation of reservoir datum relative to water supply distribution header

Q_s = net flowrate into storage via hydraulic delivery system from water distribution header, i.e., $Q_s = Q_p - Q_h$

Q_{sl} = rate of water loss from reservoir (includes seepage, evaporation, ice formation)

η_{cs} = flow-to-storage head loss factor (a function of flows in the hydraulic delivery system.

(b) Hydro-electric Generating Plant

P_h (kW) = $9.81 \times 10^{-3} \rho \eta_h \eta_{ch} Q_h h_h$, electrical output

where ρ = density of water (kg/m^3)

η_h = hydro plant efficiency (turbine, coupling, generator, transformer)

η_{ch} = generation head loss factor (a function of flows in the hydraulic delivery system)

Q_h = flow through the turbines (m^3/s)

h_h = operating head (m).

(c) Wind Turbines and Drives

P_w (kW) = $\eta_w P_m$, output power from wind turbine and drive where η_w = efficiency of conversion of wind turbine shaft power via mechanical or electrical coupling to drive power

Pm = power delivered mechanically at the wind turbine shaft or electrically at the generator (kW, a function of windspeed and the particular wind turbine).

(d) Pumps

$$Q_p \ (m^3/s) = 102 \ \eta_p \ \eta_{cp} \ P_p (\rho \ h_p)^{-1}$$, pumped flowrate

where η_p = pumping efficiency

η_{cp} = pumping head loss factor (a function of flows in the hydraulic delivery system)

P_P = input power to pumps or pump motors (kW)

ρ = density of water (kg/m^3)

h_p = pumping head (m).

(e) Load

$$P_L \ (kW) = \eta_L \ P_G$$, community electrical demand

where P_G = output power from wind/hydro-electric generating system (kW)

η_L = overall efficiency of power distribution to community end uses.

The above parameters are variously time-dependent, interrelated, and site-dependent. Interrelationships depend upon the wind/hydro system format, several being possible with the wind-turbine-and-pump combinations identified in Section 2.3. This leads to some simplification of the basic functions above, for specific cases. In addition, it is sufficient at this concept-evaluation stage to idealize further some of the parameters. The formats examined by simulation in this project are outlined in Figures 4.2 and 4.3.

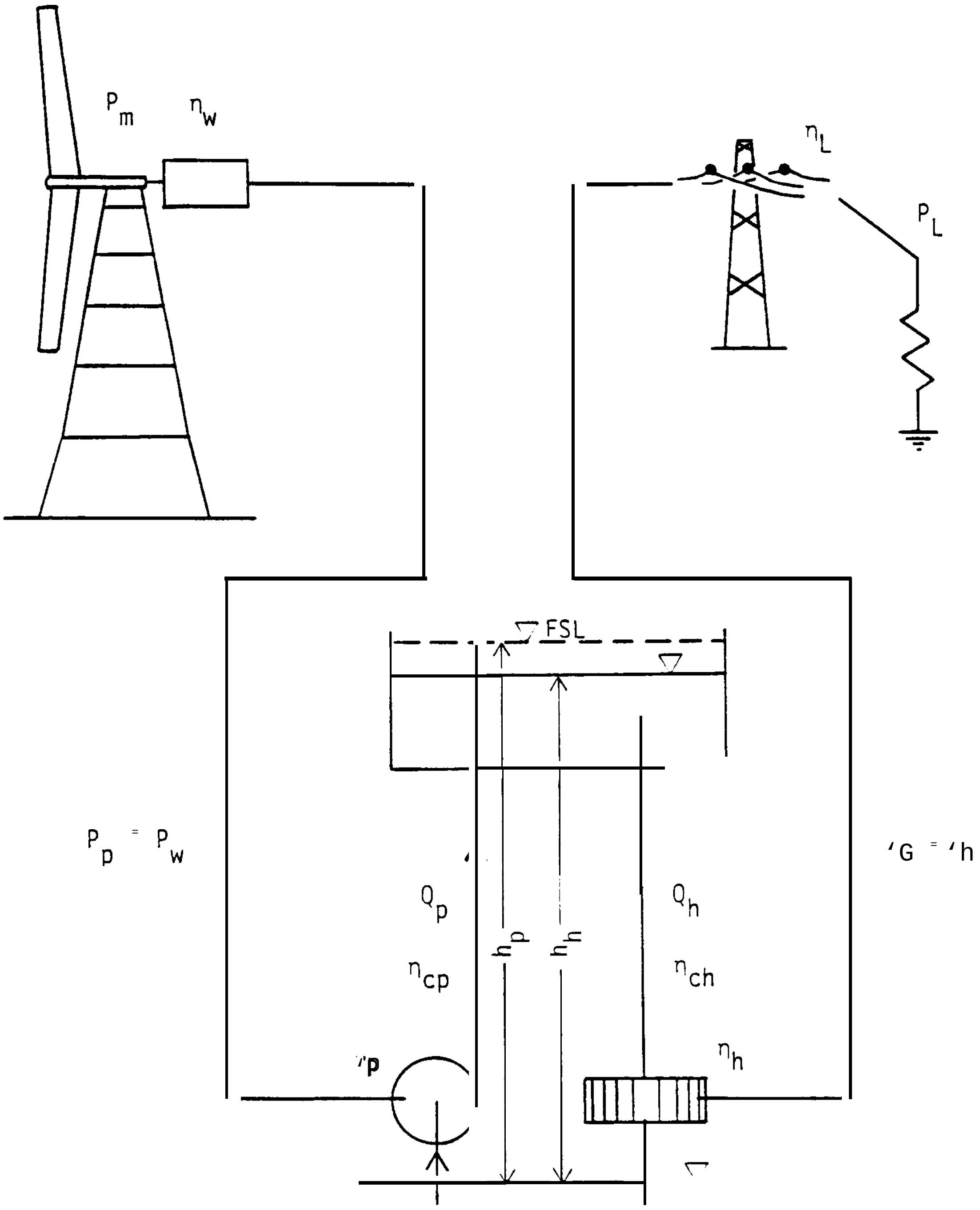


FIGURE 4.2 WIND/HYDRO SYSTEM SIMULATION - DECOUPLED MODE

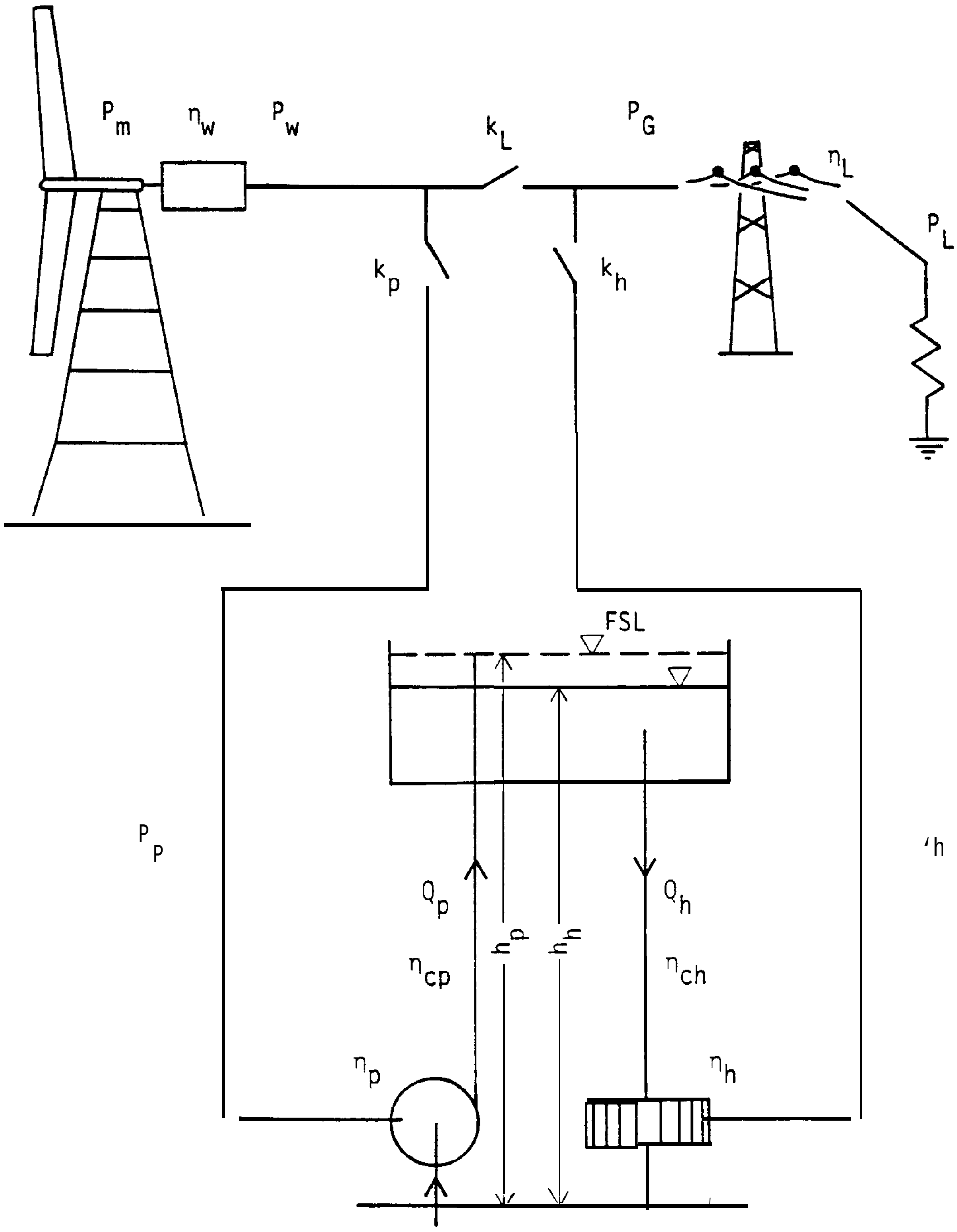


FIGURE 4.3 WIND/HYDRO SYSTEM SIMULATION - DIRECT GENERATION MODE

Simplifications made to the general system layout of Figure 4.1 to facilitate study of the three wind/hydro formats are as follows:

(a) Pumping- and hydro-station hydraulic conduits are considered to be separated systems. Solution-of operating heads at each time step in a combined hydraulic delivery system would necessitate an iterative calculation not justifiable in analysis at this stage. In terms of design, the separated system would be the simpler of the two, using only classical pump and turbine configurations. However, the combined system may be less costly and have advantages for winter operation despite the additional design and installation complications associated with a common header and conduit. Site conditions ultimately may favour one or the other hydraulic delivery scheme.

(b) The generating station tailwater elevation and the low-level water supply basin level are considered to be equal and constant. This is representative of the conceivable situation in the Northwest Territories in which a single body of water, such as a lake, would be used both for supply and discharge (a most desirable alternative, of course, would be a site allowing a high ratio of generation head to pumping head). For a larger water body, fluctuations in its water level reasonably could be neglected in comparison to a range of operating heads from approximately 10 to 150 metres. This implies that the volumes transported for use in the wind/hydro-electric supply system are small in relation to lower basin storage.

(c) Pumping head, h_p, is maintained as a constant, at the difference between upper reservoir full supply level and the water level in the lower supply basin. For design this is a constraint which would facilitate the optimal selection of pumps but would have implications for winter operation. Conceptually at least, pumped flow would be delivered at the full supply elevation of the upper reservoir, regardless of its operating level.

(a) Upper reservoir surface area, A_s, is taken as a constant, with storage directly proportional to depth of water, hs, up to V_{smax} at full supply level.

(e) Upper reservoir losses are ignored, i.e., $Q_{sl} = 0$.

(f) Friction losses in hydraulic delivery systems are not considered, i.e., $\eta_{ch} = \eta_{cp} = \eta_{cs} = 1.0$. In design, reasonable conduit sizes would be specified to restrict flow losses to a maximum of a few percent for the range of flow volumes encountered. At this level of investigation these magnitudes have little influence.

(g) Generation efficiency for the hydro-electric component is taken to be a constant value as per Section 3.1, i.e., $\eta_h = 0.80$.

(h) The difference between community power consumption and power generation, e.g., distribution losses and plant requirements, is not addressed. In isolated diesel-electric communities in the Northwest Territories, $0.80 < \eta_L < 0.95$, typically. At this stage, the distribution losses are considered to be unchanged for a wind/hydro-electric supply system, and the community load from a generation perspective (i.e., P_G) has the same characteristics as for the diesel-electric system.

(i) Risk of system subcomponent unavailability is considered to be mitigated by means of redundancy, which is the approach used commonly in isolated supply systems.

Some of the above are arbitrary choices (all would be reintroduced as eventual design considerations), but they allow study to be confined to the more important wind/hydro variables. The major design quantities, i.e., required hydro-electric generating capacity, pumping capacity, windpower capacity, and upper reservoir storage volume, are investigated in a likely Northwest Territories setting.

4.3 TYPICAL REMOTE COMMUNITY CHARACTERISTICS

4.3.1 Wind Regime

Baker Lake, as indicated in Section 2.3, is representative of the most favorable regions for wind energy exploitation in the Northwest Territories. For simulation, available Atmospheric Environment Service weather data (temperatures, barometric pressures, and windspeeds) from 20 years of observations (1964-1983) at Baker Lake were used.

Mean daily windpower records for the three characteristic wind turbines of Figure 2.3 were prepared, using hourly windspeeds and with air density correction calculated from hourly temperatures and long-term average monthly barometric pressures (effect of pressure variation is minor over time compared to influence of temperature changes). As shown in Figure 2.3 and Table 2.1, operation at Baker Lake would be at the low end of the power production range, on the average, for all three wind turbine types, with the gains made possible by the design features of any particular unit being obscured by the extremely low average output through the worst intervals.

For remaining analysis, the computed daily Baker Lake windpower record for the horizontal-axis HWP-300 is arbitrarily selected as representative for simulation of operation through the critical design period of low winds. Without modification to improve energy capture at low windspeeds, or without significantly better sites, it is clear that superiority in the higher design windspeed ranges has little relevance to wind/hydro development in the Northwest Territories. For the purpose of this study, the daily windpower record is taken to mean wind generator output or shaft power output, as the case may be.

The concept of critical period for windpower is somewhat different than its hydrologic complement because there is scarcely a limit to the amount of wind-energy capture equipment which can be installed at a site. Instead of the physical limitation to the water-based energy resource, there is an economic constraint to the number of wind turbines which can be erected.

With the assumption of no natural inflow to the upper storage reservoir, and with withdrawal from storage to hydro-electric generation in all cases mitigating the temporary deficiency in average winds, the trade-off to be provided between installed windpower and upper reservoir storage does have practical outer limits. Below a certain number of wind turbines, long-term windpower would be insufficient to maintain the long-term average withdrawal required by the hydro-electric component. There would also be a practical lower value for reservoir storage below which additional wind turbines would only fractionally decrease the refilling time following a low-wind period and would be largely unused otherwise.

The critical period for wind/hydro design at Baker Lake is selected as a several-month interval of low winds in 1974, the worst such period for wind in the 20-year record. This can be interpreted in a general way as the 1-in-20 year event. The idea of a shorter critical period with length on a scale of hours and days has little meaning because intervals of calm are both frequent and interspersed with windy periods. On the other hand, intervals of significantly below-average winds do not persist over years. It is the seasonal anomalies which most greatly affect the design of a stand-alone wind-energy storage system at Baker Lake. This type of behaviour may be observed in general at Northwest Territories sites, although the worst overall month or year in recent times varies from place to place.

It should be noted that the role of a back-up power supply for the times of failure of the wind/hydro-electric supply system is not addressed in this project. The necessary provision of emergency standby equipment, e.g., diesel-electric generation, also opens up the possibility of, for example, a wind/hydro/diesel-electric supply system, with diesel fuel used to displace some of the requirement for reservoir storage capacity.

4.3.2 Electrical Generation Requirements

The electrical load characteristics of remote communities in the Northwest Territories exhibit a general homogeneity, because most are of a similar mix of government and residential customers. Per capita consumption is greater in the larger centres, reflecting the increased level of services provided therein. Some variation in load characteristics between communities can also be linked to the minor effects of resource-based activities, such as fishing and mining. In general, however, annual per capita consumption is in the range 2500-5000 kWh with annual community load factor near 0.50 (21,22).

Mean electrical generation is set at 400 kW for wind/hydro system simulation (3.5 GWh per year), representing a typical community of 1000 people. Monthly generation as a function of average annual generation is distributed as shown in Table 4.1. This annual pattern (mean ± 20 percent) can be considered to be representative of northern remote communities of about 300-1000 people. Monthly generation is distributed evenly to all days in the month. Community load growth is not considered in the investigation.

TABLE 4.1

REMOTE COMMUNITY MONTHLY ELECTRICAL GENERATION PATTERN A

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1.2	1.2	1.2	1.0	1.0	0.8	0.8	0.8	0.8	1.0	1.0	1.2

4.4 WIND/HYDRO MODES OF OPERATION

4.4.1 General

Simulation in all cases is based on daily time steps. Daily average windpower estimates are used, calculated from hourly values as described in Section 4.3.1. Operation is considered to be uniform over each time interval (constant power production, pumped flows, and reservoir releases and spills) with changes to storage determined at the end of each interval.

The effect of starting reservoir level is negated by means of operation through a period of ample winds preceding the critical year (1574, Baker Lake). For realistic windpower/storage combinations, the preceding year (1973) at Baker Lake provides sufficient run-in experience to fill the reservoir prior to drawdown in 1974. The maximum storage requirement is the volume corresponding to the greatest drawdown during operation through the critical period, starting from the highest attained reservoir level.

If windpower is available in an interval it is used as much as allowed by the particular system. Unused windpower is wasted. If the upper-level reservoir fills, any additional pumped flow is considered to have spilled. If the reservoir is empty, hydro-electric generation is necessarily zero.

4.4.2 Decoupled Mechanical Mode

The system layout for simulation is shown in Figure 4.2. In this arrangement, wind turbines and pumps are linked mechanically as described in Section 2 of this report. All losses between wind turbine shaft and pump outlet are attributed to pump efficiency, η_p, i.e., in Figure 4.2,

$\eta_w = 1.0$, $P_p = P_m$. Pumping occurs whenever windpower is available, even if the upper reservoir is full (excess is spilled, some flow is maintained in conduits). Water is released from storage to the turbines as required by the electrical generation schedule.

4.4.3 Decoupled Electrical Mode

The system layout is shown in Figure 4.2, and is similar to the mechanical system (Section 4.4.2, above). Motor-driven centrifugal pumps are stepped into the power which is available at the wind turbines, i.e., in Figure 4.2, $\eta_w \leq 1.0$ and varies according to pump size and windspeed, $P_p \leq P_m$. Pumping occurs whenever sufficient windpower is available to supply one or more pumps. The hydro-electric generation component meets the entire community load. Any wind turbine requirements for system power are considered to be within the community load.

4.4.4 Direct Electrical Generation Mode

The system layout for simulation is shown in Figure 4.3. Several operational schemes are possible. In the simplest format, community demand is met with direct wind-electric generation. When surplus windpower is available, upper-level reservoir storage is replenished, i.e., in Figure 4.3, "switches" k_L and k_p are closed, k_h is open, and $P_p = P_w - P_G$. When windpower is insufficient alone to supply the load, the shortfall is made up from the hydro-electric subsystem, i.e., in Figure 4.3, "switches" k_L and k_h are closed, k_p is open, and $P_h = P_G - P_w$. In this mode of operation the wind-energy conversion subsystem provides a "negative" load in relation to the hydro-electric generating system, which acts in a load-following role.

4.5 PERFORMANCE CHARACTERISTICS OF WIND/HYDRO SYSTEM

4.5.1 General Results

With preliminary indications of required reservoir storages on the order of 10^6 cubic metres for the selected wind regime and community load characteristics (Section 4.3), hypothetical reservoir dimensions are defined for use in simulating system operation. In most cases a surface area of 1.858×10^6 square metres (186 hectares) is used. For trials representing development of low pumping/generating heads (e.g., 10 metres) and requiring large storage volumes, a surface area of 5.574×10^6 square metres is-used. In this way realistic reservoir drawdown scales are represented. Although the behaviour of reservoir levels over time and the consequent effects upon generating heads are, of course, sensitive to the actual reservoir storage-depth relationship, the adopted values are appropriate for investigation at this stage.

Pumping efficiencies are as defined in Section 4.2.

Hydro-electric generation capacity is assumed to be adequate to meet the load plus reserve because equipment can be chosen as desired, all reservoir inflows being assumed to be wind-generated. For a 400 kW load, with 50 percent load factor, a possible configuration could be three 400 kW units.

The findings of the wind/hydro simulation experiments are summarized in Figures 4.4 through 4.8. In general , the results are confirmation that

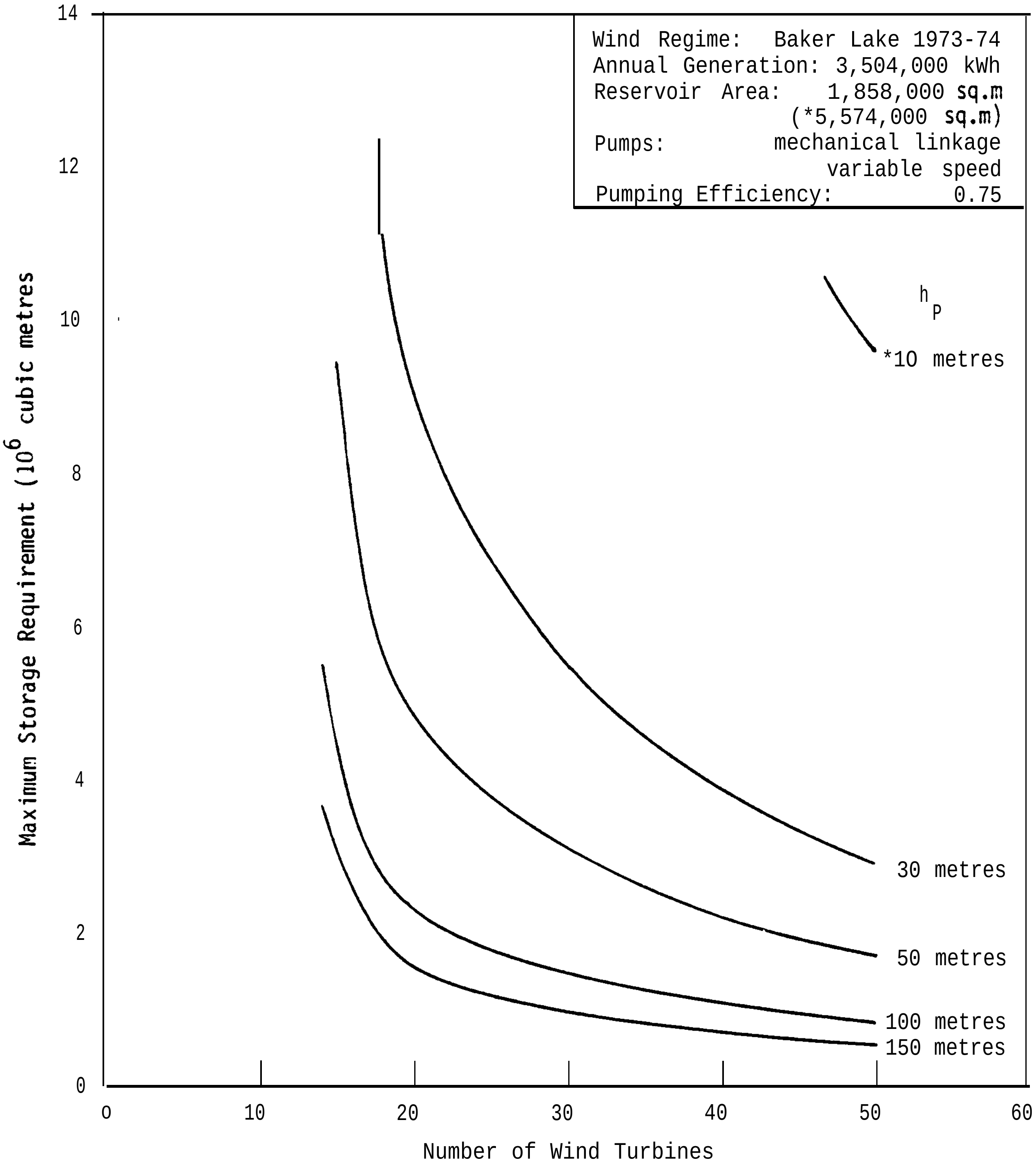


FIGURE 4.4 EFFECT OF PUMPING HEAD (DECOUPLED MECHANICAL MODE)

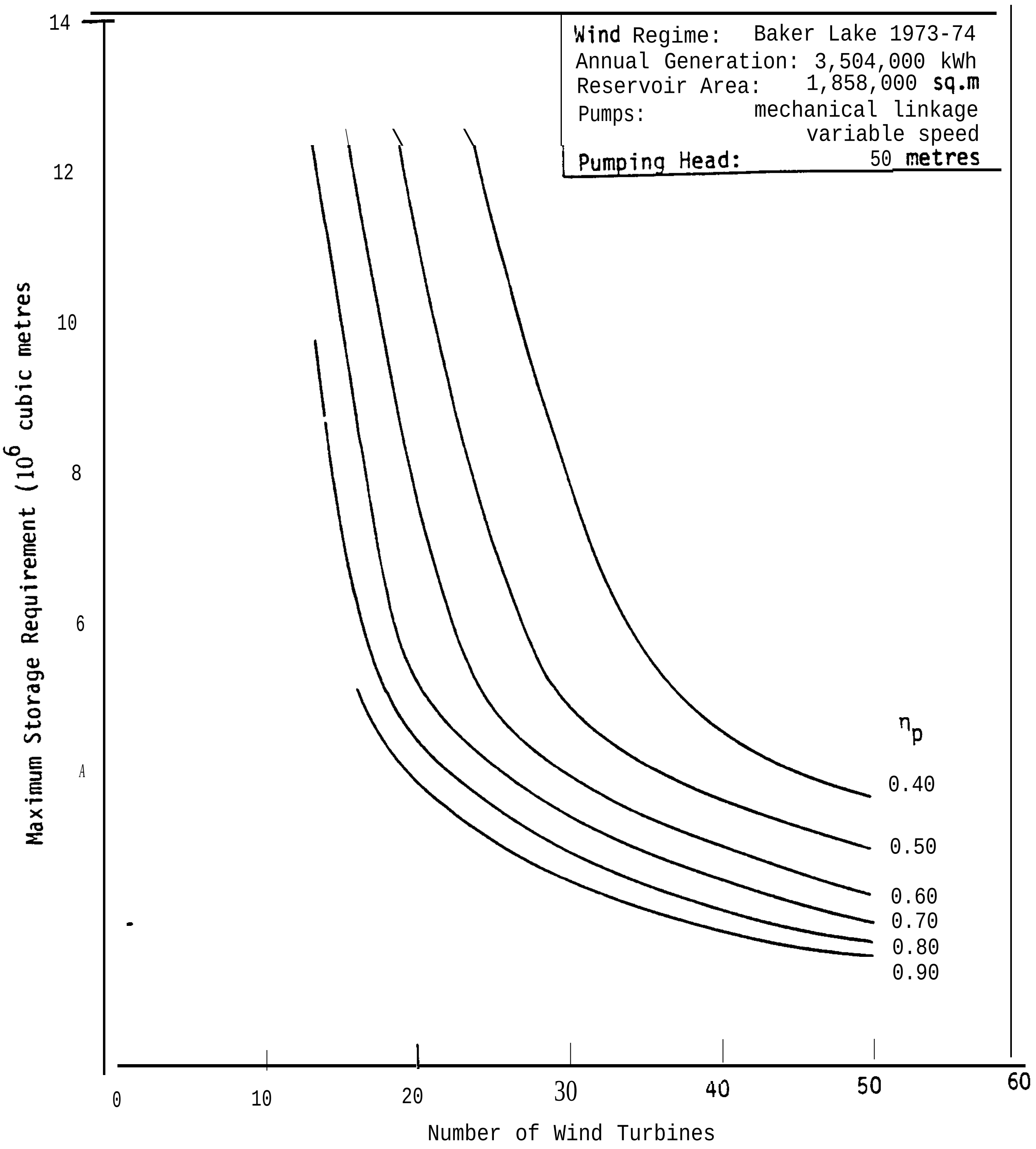


FIGURE 4.5 EFFECT OF PUMPING HEAD (DECOUPLED MECHANICAL MODE)

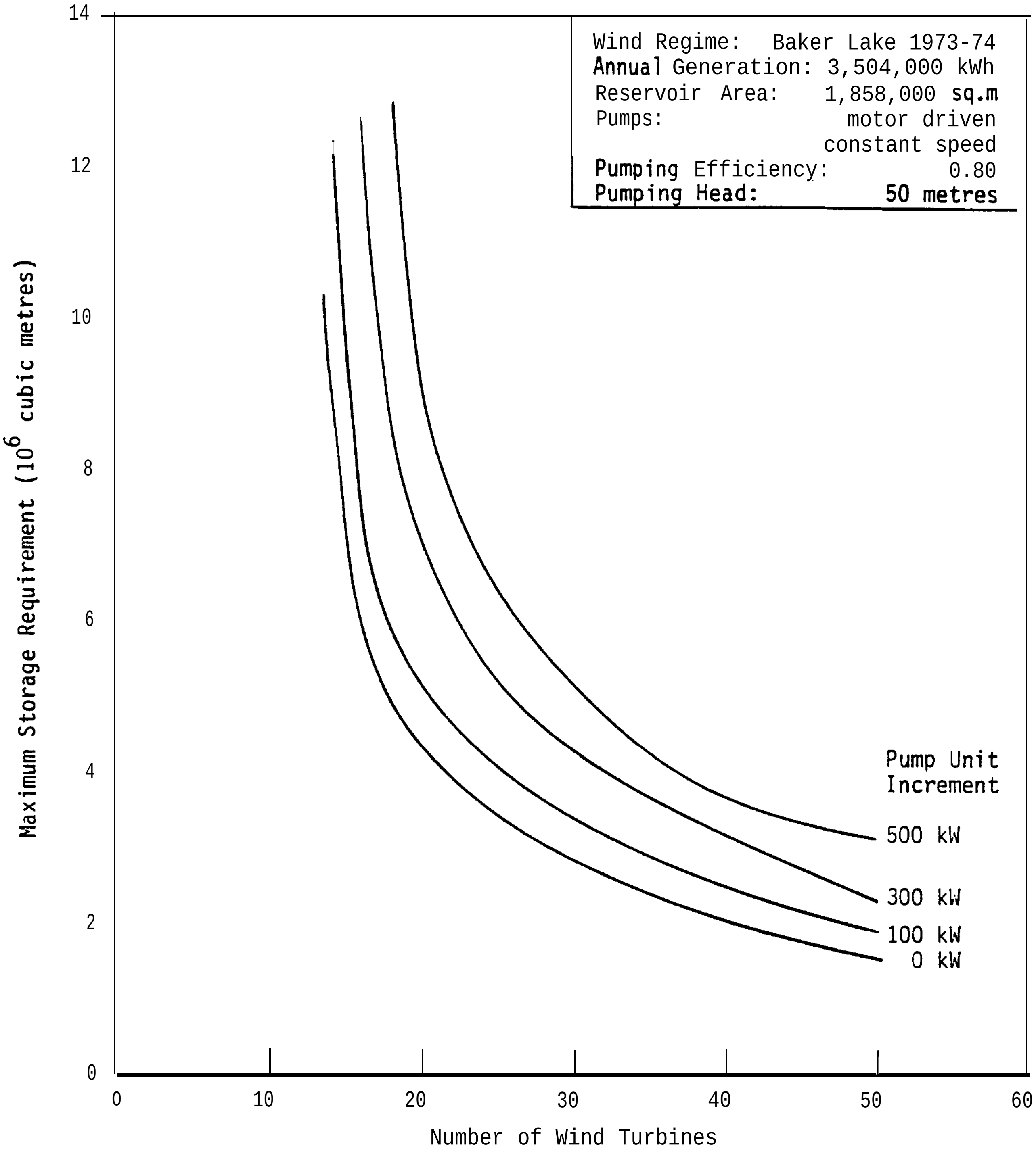


FIGURE 4.6 EFFECT OF PUMP UNIT SIZE (DECOUPLED ELECTRICAL MODE)

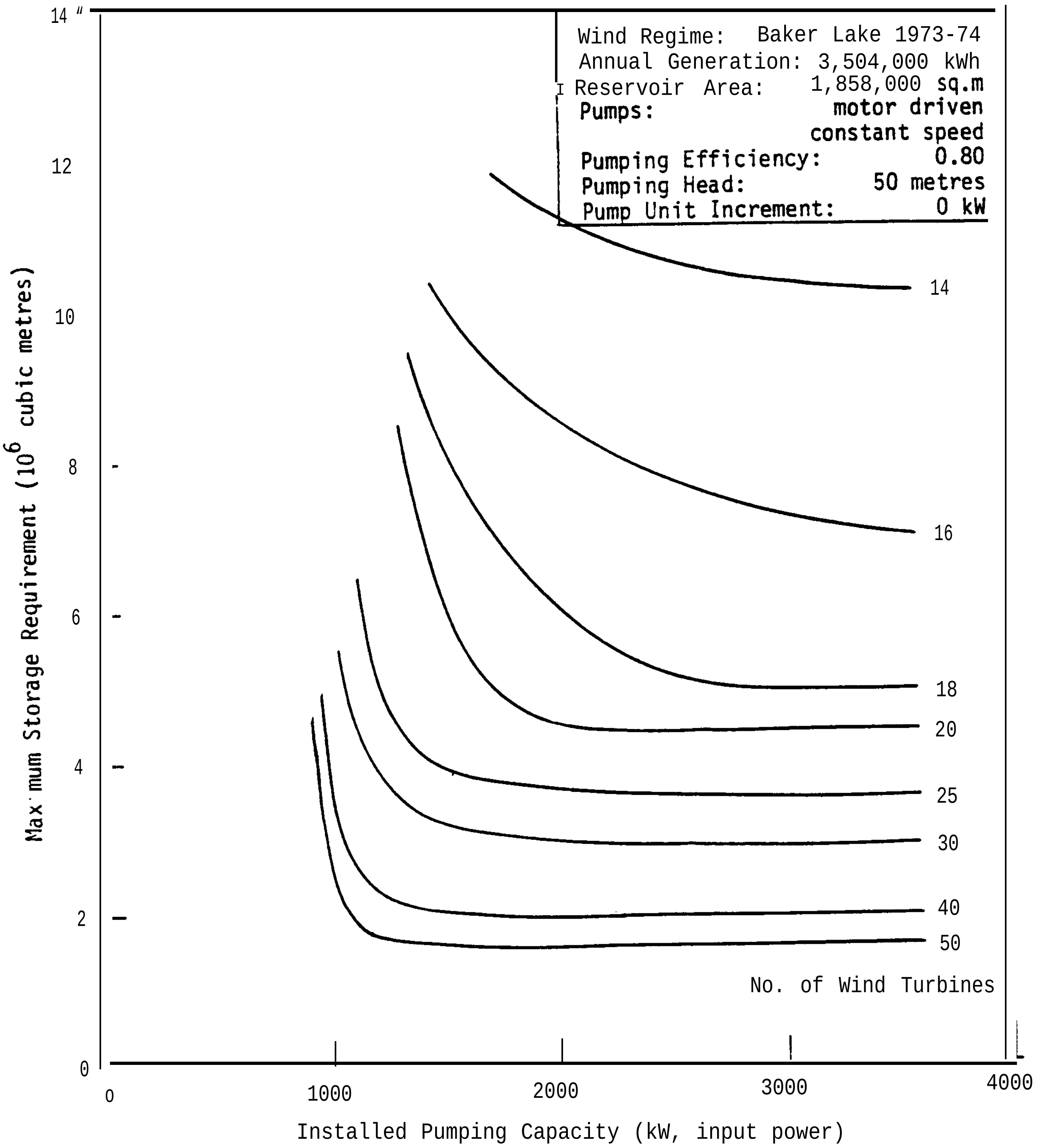


FIGURE 4.7 EFFECT OF INSTALLED PUMPING CAPACITY (DECOUPLED ELECTRICAL MODE)

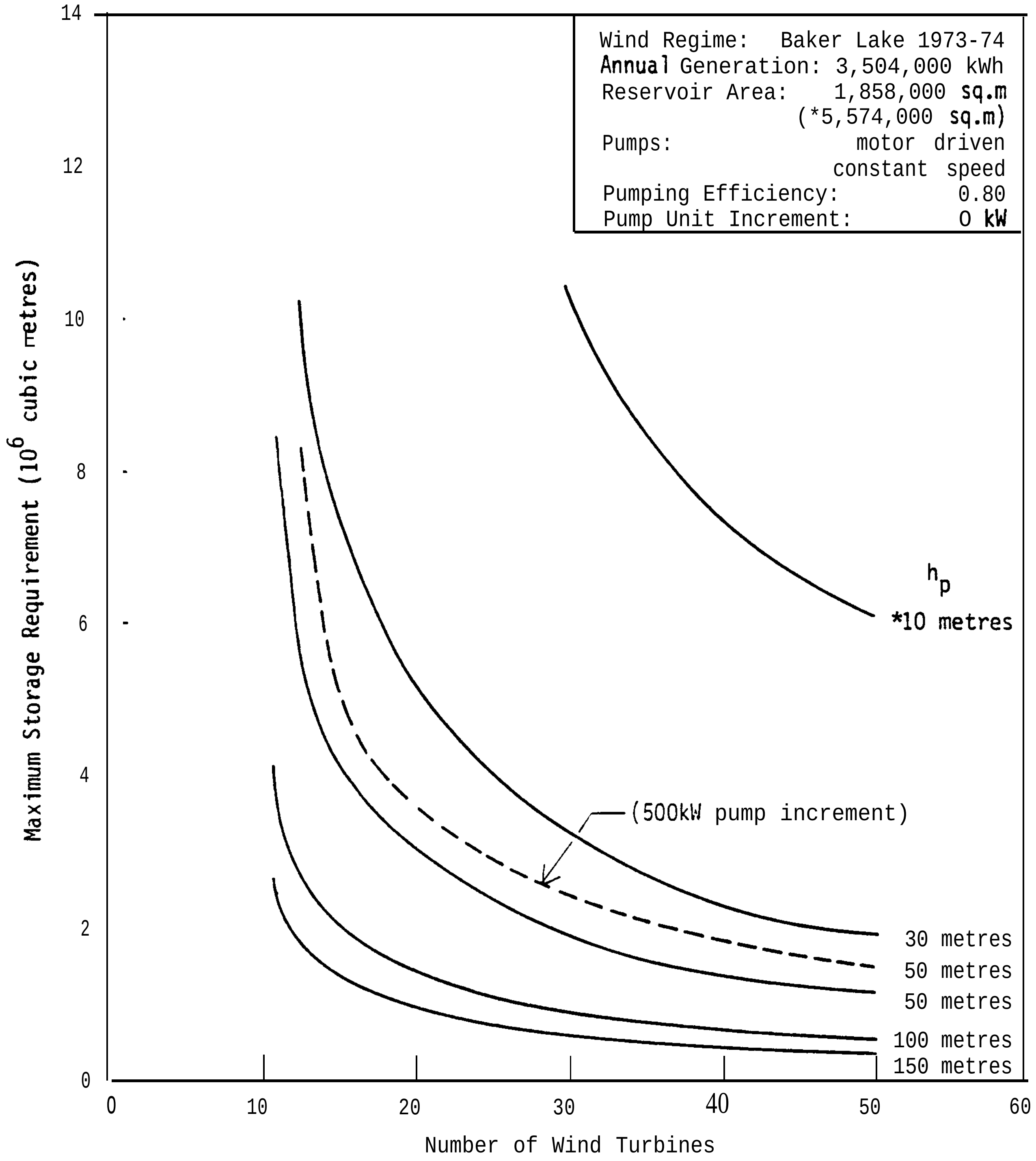


FIGURE 4.8 WIND/HYDRO SYSTEM SIMULATION IN DIRECT GENERATION MODE

the wind regimes of the most favorable Northwest Territories locations, in combination with the capabilities of contemporary wind turbines, lead to requirements for large storage reservoirs and large numbers of wind turbines for a stand-alone system.

Installed wind-energy conversion capability has been measured here in terms of nominal quantity of machines in light of the discussion in Section 4.3 in which it was concluded that a measure of wind power capacity or the like has little meaning for the wind regimes considered herein, where the periods of greatest importance are those over which wind is in short supply. As an indication of this, the 20 to 50 wind turbines shown in Figures 4.4 to 4.8 correspond to installed windpower capacities of 6000 kW to 15000 kW (HWP-300 output characteristics) in the case where the average system supply is just 400 kW. For less than approximately 20 wind turbines, the shortage of windpower becomes apparent, as storage requirements increase sharply. For larger numbers (say 50) of wind turbines, the over-supply of wind-energy conversion capability serves to refill the reservoir quickly when extended periods of drawdown are interrupted by short-lived windy periods.

4.5.2 Decoupled Pumping System

The effect on storage of the head which may be available for development is shown in Figure 4.4 for a decoupled mechanical pumping scheme (Section 4.4.2). In this system all wind turbine output energy is usable as input to the pumping system, and ample pumping capacity is provided. For heads less than 50 metres, storage volumes required for continued operation through the 1974 critical period can be mitigated only with very large installed windpower capacity.

It can be seen from Figure 4.5 that, starting from the 75 percent value observed in prototype tests for mechanically linked reciprocating pumps, a variation of 10 percent in effective pumping efficiency could make a difference of on the order of 0.5 x 10^6 cubic metres or more in storage required for the typical 50-metre head case. Because of this, and assuming wind turbine designs themselves do not change appreciably, it would be desirable to determine the expected northern performance and reliability of the rigid remote drive linkage system and the proposed continuous steel-cable drive system for moderate to large horizontal separation of wind turbines and pumps. This should precede evaluation of wind/hydro sites for applications involving mechanical linkage.

If motor-driven centrifugal pumps are used with electricity-generating wins turbines in the decoupled pumping configuration (Section 4.4.3), the effect of wasted wind energy on storage requirements is shown in Figure 4.6. The loss comes about as a result of the stepping of constant-speed pumps into the combined power output of the wind turbines. In practice this effect could be lessened by allowing the speed of some pumps to be varied within a range near the design speeds. However, with two or more sizes of pumps, a suitable firing sequence, and a supporting control system, the losses could be reduced arbitrarily. For the example of Figure 4.6, five 100 kW pumps couldbe stepped at peak under the power curve, and the remainder could be 500 kw pumps operating as base units. The power-matching losses then would be those associated with 100 kW pump increments.

The difference between decoupled mechanical and electrical pumping modes thus becomes a matter of the workability of the pump drive system for the former and the stand-alone electrical considerations for the latter. If both are technically feasible, storage requirements depend upon the net efficiency of conversion of wind turbine shaft power to pumped flow.

It has been shown that installed wind-energy conversion capability must be quite large compared to average system generation. Wind turbine power output is pooled to run a total pumping capacity which needs to be only a fraction of the installed maximum windpower output. Pumping requirements for the simulated system are shown in Figure 4.7.

For larger wind turbine installed capacity, less pumping capacity is required because adequate flow volumes can be generated even in low winds. During windy periods, windpower output may exceed available pumping capacity but the excess can be wasted without affecting storage requirements. Where installed windpower capacity is lower, more pumping capacity is required to take necessary advantage of the power available from the infrequent but higher winds. It is clear from Figure 4.7 that an increase in pumping capability has only limited effectiveness in allowing reduction of storage requirements or installed wind-energy conversion capability. As there is more than one order of magnitude difference between incremental cost of pumping capacity and that of delivered average wind turbine output power, it makes sense to install adequate pumping capacity to ensure rapid replenishment. The pumping component would not be a major factor contributing to economic viability given present wind turbine equipment costs and probable reservoir development costs.

4.5.3 Direct Generation System

Provided that electrical considerations would allow direct generation to load from wind turbines (Section 4.4.4), the reduction in storage requirement or wind turbine installed capacity which could be effected by the system examined herein is shown in Figure 4.8 to amount to 30 to 40 percent for the wins regime, load, and range of heads considered. The amount of wasted windpower which goes along with fixed pump sizes is also reduced. With much of the wind energy not passing through the hydraulic subsystem on its eventual way to the load, this is to be expected.

Used essentially as a peaking plant, the hydro-electric subsystem is called upon frequently, but usually only for short durations, because winds exceeding cut-in speeds occur often (as indicated, these are about the same as long-term average windspeeds for Baker Lake and other favorable Northwest Territories sites). From the power *curves* of Figure 2.3 it can be seen that there is only a narrow transitional band of operation over which it may be reasonable to utilize both wind and hydro components simultaneously. The reason is the large number of wind turbines which are needed to refill the reservoir following a period of relative calm are also able to satisfy the entire demand with their combined output at windspeeds only slightly above cut-in speed. It would perhaps require a simpler control system if a particular windspeed value were selected for a complete changeover from hydro-electric generation to direct wind generation. Some increase in required reservoir storage over that indicated in Figure 4.8 could be expected to result from an operating scheme of this type, but this is not investigated further herein.

4.6 SUMMARY OF SIMULATION FINDINGS

The primary factors for wind/hydro system design for the Northwest Territories, assuming present equipment, are (a) the durations of periods of low winds relative to long-term averages, and (b) the operating ranges of wind-energy conversion systems relative to the range of windspeeds found at a site. For the case examined, low windspeeds occur over an extended period through which wind turbines are unable to capture much energy. The effect is a hydro-electric supply subsystem storage requirement equivalent to approximately 0.5 to 1.8 average-power months (400 kW, hydro-generation efficiency 0.8, storages normalized for head). This range of storage depends on the operating mode and installed wind-energy conversion capability. The wind turbine requirement is approximately 15 to 40 intermediate-scale units with the typical power output characteristics which were used in the trials.

The cost of equipment and construction for a suitable combination of storage and wind turbines could be very high. The results of Section 4.5 are specific to one wind regime (Baker Lake) and load (400 kW, average monthly generation given by Table 4.1), but wind records for Baker Lake exhibit month-to-month patterns similar to those of other favorable sites in the Northwest Territories. The community load used is also reasonably typical of remote northern diesel-electric supply systems. The factors which are described above as having most influence on wind/hydro system design in the context of this project therefore may make impractical the concept of a stand-alone system for remote communities using wind energy as the sole source.

A fair assessment of the more logical wind/hydro configurations which have been suggested from review of the progress of wind-energy conversion system development would depend upon the results of further advances by the industry. In particular, experimentation with drive systems which allow flexibility in remote siting of wind turbines and pumps would enhance appreciation of the viability of variable-speed operation and the extraction of mechanical energy from the wind turbine shaft. The use of a.c. wind generators for isolated electricity-supply systems could be facilitated with further application of improved static power converters. Once technical feasibility is reasonably well assured, and candidate wind/hydro system formats identified with confidence, then economic aspects of installations may be investigated.

SECTION 5

5.0 ASSESSMENT AND DIRECTION

5.1 CONCLUSIONS: AUTONOMOUS WIND/HYDRO POWER SUPPLY

The discussion of technical considerations in the preceding sections of this report suggests that the appropriateness of demonstration of a stand-alone wind/hydro-electric supply system for a remote Northwest Territories community depends upon further development and experimentation by the windpower industry. In particular, the technical development of critical components has not yet advanced to the point where it is clear which are the most attractive approaches for using wind energy conversion devices to provide source energy in an isolated system. This may be attributed primarily to the fact that wind power development has, with few exceptions, concentrated on electricity-generating systems for grid interconnection applications.

Economic viability of stand-alone wind/hydro systems in the Northwest Territories is likely to be impeded by the ramifications of the wind regimes to be found at even the most favorable sites, although the site-dependent nature of the hydro-electric subsystem could have the greater impact on costs. It would be appropriate to initiate economic evaluation for specific sites once the workability of the various wind-energy conversion and pumping schemes was understood. In general, however, it is characteristic of the wind regimes that there would be intervals, extending into weeks and months, over which total wind-energy capture would be affected by sustained low wind-energy availability. To make up for the resulting short-term production averages compared to long-term average output, there would be a requirement for a combination of additional wind-energy conversion capacity (greater installed wind turbine swept area, or number of units) and extended reservoir storage capacity. The results of this study indicate that the nature of the periods of relative calm in the Northwest Territories would necessitate installation of large wind-energy conversion capacities and reservoir storages relative to the magnitudes of the isolated loads to be supplies.

Notable are the following among the findings which have arisen from the review of windpower developments, and from the simulation of wind/hydro systems using a selected wina turbine power output curve and a typical Northwest Territories community load aria-wind regime:

(a) The range of wind turbine types under development includes several fundamentally different designs. In the larger sizes suited to applications at the community level, the wins-energy capture performance varies among the lightweight horizontal- and vertical-axis wind turbines and multi-bladed low-speed horizontal-axis machines. However, these differences are sufficiently small that each of the three major types may be considered for wind/hydro applications. Factors other than power output are likely to be more important in the determination of suitability.

(b) Long-term average windspeeds at the most favorable of locations in the Northwest Territories are near the cut-in windspeeds for available 100 kW-or-greater wind turbines. Idle periods for such units would be frequent, and maximum wind-energy conversion capacities would rarely be utilized. Within reasonable distances of communities, however, there may be some sites at which average windspeeds are somewhat greater than regionally recorded values, due to the effect of the local topography.

(c) Short-period average windspeeds are significantly lower than long-term averages. Wind-energy production ever such intervals would be very poor. The reservoir storage requirement for the simulated systems and representative wind turbine output used begins at approximately

0.5 to 0.8 average-power months and ranges up to several months, depending on the efficiency of conversion of windpower to pumped flow and on the system layout. The corresponding required windpower capacity begins at 15 to 25 units for the representative wind turbine characteristics used (per unit: 300 kW capacity, 380 square metres swept area). This result is specific to the wind regime at Baker Lake but is sufficient to indicate that, for a typical Northwest Territories site and load, an average output of 400 kW from a wind/hydro-electric system would require a large storage reservoir and wind turbine swept area.

(d) Topography at a potential reservoir site would determine the storage vs. head characteristics and maximum usable storage range which could be developed. For the various wind/hydro system configurations examined in the project, concept-level simulation confirms that required storage volumes span the same order of magnitude for all systems.

The two major pumping systems considered were:
(i) reciprocating pumps mechanically driven directly from the wind turbine rotor shaft, and
(ii) motor-driven centrifugal pumps with electric power originating from wind-electric generators.

The two major system layouts examined were:
(i) the load being met by the hydro-electric supply system, with wind energy being used only for pumping to the reservoir, and
(ii) the local load and pumping load being met by wind-generated electric power with supplementary or back-up capacity being provided from the hydro-electric subsystem.

Somewhat less storage is required with the latter direct generation configuration in which the hydro-electric subsystem acts in a load-following role.

The factors which would dominate system sizing, with any of the formats, are:
(i) the lower mean windspeeds in the Northwest Territories relative to available wind turbine operating ranges, and
(ii) the duration and succession of critical periods with below-normal winds.

(e) Operation of wind-energy conversion equipment in cold weather has been demonstrated, but experience with the severity of conditions which are common and prolonged in the Northwest Territories is limited. It may be that some materials and sub-component designs used for the equipment now being developed and commercialized would need to be substituted or revised for northern installations.

(f) Further study is required into the feasibility of using lightweight wind generators to supply a.c. power directly to load and/or to motor-driven pumps without system support or with only the support of an isolated hydro-electric subsystem in which total hydro-generator rating is several times smaller than the total installed wind-generator rating. The ratio of wind turbine capacity to load-following equipment capacity has been much less than this in studies to date of grid-connected applications and, for example, wind-diesel hybrids for remote communities. Development of and experience with static power converters for constant- and variable-speed applications with synchronous and induction wind generators may lead to viable equipment for stand-alone wind/hydro systems.

(g) Operating experience with large wind turbines and mechanically coupled pumps is limited. With good starting torque and low cut-in speeds, large-bladed low-speed units are attractive for areas of poorer wind energy potential. An obstacle to adoption of mechanical wind-energy conversion systems is the likely need for physical separation of wind turbines and pumps, due to lack of coincidence of a favorable wind site with a source of water for pumping. As optimal siting appears to be of primary importance for Northwest Territories applications to ease the disadvantage of the lower wind energy potential, development of efficient remote drives would be required. A rigid reciprocating linkage for smaller separations has reached the prototype stage. A low-speed continuous-steel-cable drive system to run reciprocating pumps at some distance from large wind turbines, or in difficult terrain, has been proposed but has not as yet been demonstrated.

(h) Design of the hydro-electric generating station, transmission tactilities, and hydraulic delivery system for a wind/hydro scheme would be relatively straightforward and site-dependent, given that the problem of providing firm flow for the turbines must be part of wind-energy conversion subsystem considerations. Installed capacity, including reserve capacity and number of units, is related only to firm energy requirements, load shape, and reliability. Low-temperature protection would be an important feature of design, particularly if the site configuration was not amenable to combining reservoir supply and return conduits. Some windpower could be dedicated, or surplus storage could be drawn upon, to provide power for heating of the hydraulic delivery system or for pumping to keep it open. Study of other means of preventing freezing problems in the hydraulic subsystems would be warranted once the direction to be taken by the industry for wind/hydro applications is clarified.

The stand-alone wind/hydro-electric supply system concept is concluded to be insufficiently advanced in some areas at this time to support a demonstration project in the Northwest Territories. Fundamental developments are required in the area of wind-energy conversion equipment and controls, so that experimental autonomous windpower-and-hydropower combinations can be subjected to trial. Once favorable performance is achievable, then the technical and other problems associated with installation in the north can be addressed and expected costs can be compared to these of alternative electrical supply systems.

5.2 RECOMMENDATIONS: WINDPOWER IN THE NORTHWEST TERRITORIES

5.2.1 Diversification of Small Power Supply Systems Using Windpower

The fluctuation of power output due to variability of an energy source such as wind can be reduced through use of suitable storage. For the stand-alone wind-based electricity-supply system in the Northwest Territories, the storage requirement has been concluded to be large relative to demand in the isolated local network. Diversification of the system could decrease the amount of storage needed for a given reliable power output, but, for a wind-only source, this implies a geographical diversity of generating sites which would extend to more than one major weather regime to reduce the periods of zero windpower generation. However, for the isolated loads of the Northwest Territories, the required interconnection of communities is not a viable possibility.

Local diversification, however, is an alternative which merits further investigation. With wind energy utilized in a supplementary or fuel-saving role, physical and network constraints are much less severe than for a wine-dominated supply system, and the technology appears to be able to support expansion of the trials already underway in the Northwest Territories to include additional wind-energy conversion configurations.

Existing hydro-electric developments in the Northwest Territories are located inland in an area of poor wind energy potential, but the value of additional hydro generation in the hydro/diesel systems may nevertheless justify implementation of reservoir storage augmentation using wind-powered pumping. Both the multi-bladed high-torque wind turbines mechanically linked to pumps and grid-connected wind generators and pumps could be considered for the application, the latter perhaps allowing more flexibility in locating equipment. As this would be an application of technology for which some operating experience has been accumulated elsewhere (e.g., mechanically linked prototype wind-pumping system at Calgary, A'lberta; electrically interconnected pumping system at Wreck Cove, Nova Scotia), a realistic assessment of economic viability could be made. For an identified site, set-up, operating and maintenance, and capital costs could be projected relatively closely.

The questions associated with (a) mechanical linkage of separately located pumps and wins turbines, (b) output power quality from wind-electric generators, and (c) operation in the north, would still have to be resolved. Because of this, it would be advisable to consider experimental scales only for an initial project in the Northwest Territories.

For remote Northwest Territories locations having only limited potential for hydro-electric development due to insufficient firm flow, it may be possible to formulate a viable power supply system in which the dependable hydro-electric energy is enhanced, either through displacement of storage withdrawals by direct wind-electric generation, or through augmentation of storage using wind-powered pumps. As above, diesel generation could also have a role.

Finally, the local diversification could most directly take the form of an electrical or mechanical interconnection of wind turbines with the small diesel-electric supply system. Fuel-saving would be the intended mode of operation. Base load, peaking capacity, and reserve requirements would be unchanged from the conventional diesel-electric system. Field trials with vertical-axis wind turbines in conjunction with diesel generation have been ongoing at Sudbury, Ontario (wind-diesel hybrid), and, for example, at Churchill, Manitoba, and Cambridge Bay, Northwest Territories.

5.2.2 Recommendations

Wind turbines to supplement other electricity-supply schemes in northern communities must be more cost-effective than the most attractive alternative, which is currently diesel generation in most cases. Some experience with wind turbines is being acquired but much of the cost is still related to the development effort. The less-than-optimal wind regimes near remote population centres in the Northwest Territories also discourage immediate acceptance of wind-energy conversion options. The following suggestions therefore may be made:

(a) For northern applications, basic field experience with wind turbines is required to establish and/or verify performance characteristics. These would include maintenance requirements, materials suitability and durability, reliability and availability, upgraded estimates of expected service life, actual energy capture and delivery, practical network penetration levels and the accompanying degradation of power quality (wind-electric turbines), pumping effectiveness and hydraulic fluid behaviour at low field temperatures (mechanical and electrical pumping schemes). Trials should be considered to be experimental; consequently, the wind turbines need only to be of sufficient size to be instructive representations of full-scale units when exposed in the northern environment.

(b) The application for pumping in an experimental installation in the Northwest Territories need not be that of replenishing a hydro-electric storage reservoir, the number of suitable existing developments being limited. Rather, the possibility of implementation of wind-powered pumping for remote community water supplies could also be investigated. Small-scale trials could serve the dual purpose of providing improved availability of water fcr consumption as well as operating experience with wind turbines in isolated northern settings.

(c) Identification of anomalous sites near remote communities where significant local acceleration of wind occurs should be undertaken prior to field testing of any but experimental wind turbines. Such sites tend to be missed in studies of regional wind-energy potential, but could turn out to be attractive locations for wind turbines, depending on future costs for energy alternatives. At promising sites, some quantification of energy availability should be initiated, logically through short-term wind monitoring. Transmission distance to the community should be respected in the investigation of sites.

(d) As a first step in further investigation of hydro-electric possibilities complemented by windpower and/or diesel generation for remote communities, it is advised to study the interrelationships between natural flows and winds at or near representative Northwest Territories locations in order to gain an understanding of the implications of shortages of wind and/or water for system design and operation.

SECTION 6

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APPENDIX A

APPENDIX A

A.0 CHARACTERISTICS OF SELECTED WIND TURBINES

A.1 INTERMEDIATE-SCALE WIND TURBINE GENERATORS

Producer: DAF Indal Ltd., 3570 Hawkestone Road,
Mississauga, Ontario L5C 2V8

Model: Series 6400-500
Rotor: Vertical axis, Darrieus
36.6 x 24.4 metres, 595 square metres swept area
2 blades
45 rpm
Equator height: 21.3 metres
Generator: 500 kW, Induction

Producer: Flow Industries, Inc., 21414 68th Avenue South,
Kent, Washington 98031

Model: Model 100
Rotor: Vertical axis, Darrieus
22.8 x 16.8 metres
2 blades
50 rpm
Generator: 100 kW

Producer: VAWTPOWER, Inc., 134 Rio Rancho Drive,
Rio Rancho, New Mexico 87124

Model: VAWTPOWER 185
Rotor: Vertical axis, Darrieus
25.0 x 18.3 metres
2 blades
48 rpm
Generator: 185 kW

Producer: Dansk Vindteknik A/S,
Strandholtvej 24,
Skellerup, Danmark
Model : 265
Rotor: Horizontal axis
660 square metres swept area
42 rpm
Generator: 265 kW

Producer: James Howden and Company,
195 Scotland Street
Glasgow, U.K. G5 8PJ
Model : HWP-300
Rotor: Horizontal axis, upwind
380 square metres swept area
3 blades
45 rpm
Hub height: 22 metres
Generator: 300 kW, Induction or Synchronous

Producer: Westinghouse Electric Corp.,
875 Greentree Road
Bldg. 8, 4th Floor
Pittsburgh, Penn. 15236
Model : WWG-0500
Rotor: Horizontal axis, downwind
1140 square metres swept area
2 blades
42 rpm
Hub height: 30.5 metres
Generator: 500 kW, Induction or Synchronous

Producer: WTG Energy Systems, Inc.,
251 Elm Street
Buffalo, New York 14203
Model : MP-200
Rotor: Horizontal axis, upwind
467 square metres swept area
3 blades
30 rpm
Generator: 200 kW, Induction or Synchronous

Model : MP-600
Horizontal axis, upwind
1140 square metres swept area
3 blades
25 rpm
Hub height: 33.5 metres
Generator: 600 kW, Induction

Producer: Carter Wind Systems,
P.O. Box 684
Burkburnett, Texas 76354

Model : 125
Rotor: Horizontal axis, downwind
299 square metres swept area
2 blades
75 rpm
Hub height: 36.5 metres
Generator: 125 kW, Induction

Model : 175
Rotor: Horizontal axis, downwind
308 square metres swept area
2 blades
75 rpm
Hub height: 36.5 metres
Generator: 175 kW, Induction

Model : 200
Rotor: Horizontal axis, downwind
308 square metres swept area
2 blades
125 rpm
Hub height: 48.8 metres
Generator: 200 kW, Induction

Producer: California Energy Group, Inc.,
3500 South Susan Street
Santa Aria, California 92704

Model : Turbowind 64
Rotor: Horizontal axis, downwind
299 square metres swept area
3 blades
52 rpm
Generator: 125 kW, Induction

Producer: North American Power Corp.,
240 West Shaw Avenue, Suite D
Clovis, California

Model : 95
Rotor: Horizontal axis
660 square metres swept area
Generator: 300 kW

A.2 INTERMEDIATE-SCALE WATER-PUMPING WIND TURBINE

Producer: Deltx WINDPUMP Corp.,
305 Mount Royal Village
1550 8th Street SW
Calgary, Alberta T2R 1K1

Model : WP65
Rotor: Horizontal axis, upwind
308 square metres swept area
8 delta blades
Approx. 7 to 30 rpm
Drive: Mechanical coupling to 2 reciprocating pumps
Variable stroke length
output: 198 kW maximum at rotor shaft
148 kW maximum pump output

A.3 PROTOTYPE MEGAWATT-SCALE WIND TURBINE GENERATORS

Producer: Boeing Engineering and Construction Company
Project: MOD-2
Rotor: Horizontal axis
6567 square metres swept area
2 blades
17.5 rpm
Hub height: 60.9 metres
Generator: 2500 kW, Synchronous

Producer: Hamilton Standard
Project: WTS-4
Rotor: Horizontal axis
4803 square metres swept area
2 blades
30 rpm
Hub height: 80 metres
Generator: 4000 kW, Synchronous

Producer: DAF Indal Ltd.
Project: EGLE
Rotor: Vertical axis, Darrieus
4000 square metres swept area
2 blades
14.25 rpm
Equator height: 55 metres
Generator: 4000 kW, Synchronous