Energy Evaluation of Feeds for Pigs: Consequences on Diet Formulation and Environment Protection[1]

Jean Noblet, INRA - UMR SENAH, 35590 Saint Gilles, France
Jean.Noblet@rennes.inra.fr

Introduction

The cost of feed is the most important cost in pig meat production (about 60%), and the energy component represents the greatest proportion. Therefore, it is important to estimate precisely the energy value of feeds, either for least-cost formulation purposes or for adapting feed supply to energy requirements of animals. Evaluation of energy content of pig feeds is usually based on their digestible (DE) or metabolizable (ME) energy contents. However, the closest estimate of the "true" energy value of a feed should be its net energy (NE) content which takes into account differences in metabolic utilization of ME between nutrients. In addition, NE is the only system in which energy requirements and diet energy values are expressed on a same basis which should theoretically be independent of the feed characteristics. At each step of energy utilization (DE, ME or NE), different prediction methods can be used. An energy system corresponds then to the combination of one step of energy utilization and one prediction method. The objectives of this review paper are 1/ to consider the main factors of variation of digestive and metabolic utilization of energy in pig feeds, 2/ to present the available energy systems for pig feeds with emphasis given to NE systems, 3/ to compare the energy systems and 4/ to evaluate their ability for predicting pigs performance. Methodological aspects of energy evaluation of pig feeds and complementary information have been considered in previous reviews (Noblet and van Milgen, 2004).

Energy utilization

Digestive utilization

For most pig diets, the digestibility coefficient of energy (DCe or DE : gross energy ratio) varies between 70 and 90% but the variation is larger for feed ingredients (10 to 100%; Sauvant et al., 2004). Most of the variation of DCe is related to the presence of dietary fiber (DF) which is less digestible than other nutrients (<50% vs. 80-100% for starch, sugars, fat or protein; Table 1) and reduces the apparent fecal digestibility of other dietary nutrients such as crude protein and fat (Le Goff and Noblet, 2001). Consequently, DCe is linearly and negatively related to the DF content of the feed (Table 2). The coefficients relating DCe to NDF are such that NDF or DF essentially dilute the diet. In other terms, even though DF is partly digested by the young growing pig, it provides very little DE to the animal (Noblet and van Milgen, 2004). The digestive utilization of DF varies with its botanical origin with subsequent variable effects of DF on dietary energy digestibility. The DCe prediction equations presented in Table 2 represent therefore average equations for mixed feeds. They should not be applied to raw materials where specific relationships are to be used (Noblet and Le Goff, 2001; Noblet et al., 2003).

Digestibility of energy can be modified by technological treatments. Pelletting, for instance, increases the energy digestibility of feeds by about 1%. However, for some feeds, the improvement can be more important and depends on the chemical and physical (particle size) characteristics of feeds. In the examples given in Table 3, the improvement in energy digestibility was mainly due to an improved digestibility of fat provided by corn or full-fat rapeseed. Consequently, the energy values of these ingredients depend greatly on the technological treatment. In the specific situation of high-oil corn (7.5% oil), pelletting increased the DE content by approximately 0.45 MJ per kg (Noblet and Champion, 2003); for coarsely ground full-fat rapeseed, the DE values were 10.0 and 23.5 MJ DE/kg DM as mash and after pelletting, respectively.

[1] Adapted from presentations at the Eastern Nutrition Conference organised by the Animal Nutrition Association of Canada, May 2005 in Montreal, Canada and the Nutrition Conference organized by Lohmann Animal Health, November 2005 in Cuxhaven, Germany.

Table 1: Digestibility of fiber fractions and energy in high fiber ingredients in growing pigs (G) and adult sows (S)

	Wheat bran		Corn bran		Sugarbeet pulp	
	G	S	G	S	G	S
Digestibility coefficient (%) of						
Non-starch polysaccharides	46	54	38	82	89	92
Non cellulose polysaccharides	54	61	38	82	89	92
Cellulose	25	32	38	82	87	91
Dietary fiber	38	46	32	74	82	86
Energy	55	62	53	77	70	76

Table 2: Effect of diet composition (g/kg dry matter) on energy digestibility (DCe, %), ME:DE coefficient (%) and efficiency of utilization of ME for NE of mixed diets for growth (k_g %) and for maintenance (k_m %)[a]

	Equation	RSD[b]	Source[c]
1	DCe = 98.3 - 0.090 x NDF	2.0	1
2	DCe = 96.7 - 0.064 x NDF	2.2	1
3	ME/DE = 100.3 - 0.021 x CP	0.5	1
4	k_g = 74.7 + 0.036 x EE + 0.009 x ST - 0.023 x CP - 0.026 x ADF	1.2	2
5	k_m = 67.2 + 0.066 x EE + 0.016 x ST	1.9	3

[a] CF: Crude Fiber, CP: crude protein, NDF: Neutral Detergent Fiber, EE: ether extract, ST: starch, ADF: Acid Detergent Fiber.
[b] Residual standard deviation
[c] 1: Le Goff and Noblet (2001) (n=77 diets ; equations 1 and 3 in 60 kg growing pigs and equation 2 in adult sows, respectively) ;
2: Noblet et al. (1994) (n=61 diets ; 45 kg pigs);
3: Noblet et al. (1993) (n=14 diets; maintenance fed adult sows).

Table 3: Effect of pelletting and particle size on digestibility coefficient (%) of fat and energy in growing pigs

	Mash	Pellet
Corn-soybean meal diets[a]		
Fat	61	77
Energy	88.4	90.3
Wheat-soybean meal-full fat rapeseed diets[b]		
Fat	27	84
Energy	73.1	87.4
Wheat-soybean meal-full fat rapeseed diets[c]		
Fat	81	86
Energy	85.5	87.6
Wheat-corn-barley-soybean meal diets: Energy[d]	75.8	77.3

[a] Mean of three diets containing 81% corn and 15.5% soybean meal (Noblet and Champion, 2003).
[b] One diet containing 60% wheat, 15% soybean meal and 20% full fat rapeseed; rapeseed was coarsely ground (Skiba et al., 2002).
[c] One diet containing 60% wheat, 15% soybean meal and 20% full fat rapeseed; rapeseed was finely ground (Skiba et al., 2002).
[d] Mean of 4 diets also containing variable amounts of fibre rich ingredients (wheat bran, sugar beet pulp) (unpublished data)

Energy digestibility is affected by other factors than those related to the diet itself. In growing pigs, DCe increases with increasing BW (Noblet et al., 2003). The largest effect of BW is observed when adult sows and growing pigs are compared (Le Goff and Noblet, 2001). In addition, the difference due to BW increase is most pronounced for high fiber diets or ingredients (Equations 1 and 2 in Table 2; Table 4). This improvement in energy digestibility with increasing BW is due to the greater digestibility of the DF fraction (Table 1) related to a greater hindgut digestive capacity in heavier pigs and, more importantly, a slower rate of passage in the digestive tract (Le Goff et al., 2002). The attenuated negative effects of DF on protein and fat digestibility (i.e., reduced endogenous losses) also contribute to the reduced effect of DF on DCe in adult pigs. Therefore, the negative effect of dietary fiber on DCe becomes smaller for heavier pigs or adult sows and the contribution of DF to energy supply becomes largely positive in heavier pigs. From a large data set of measurements (77 diets), Le Goff and Noblet (2001) calculated that one g of NDF provided 3.4 and 6.8 kJ in 60 kg growing pigs and mature sows, respectively. From the same data, it was also shown that the DE difference between adult sows and growing pigs is proportional to the amount of indigestible organic matter as measured in the growing pig (4.2 kJ/g on average; Noblet and Tran, 2004).

The DCe or the DE differences between sows and growing pigs, for a given level of dietary fiber, also depend on the origin of DF or on the physico-chemical properties of DF. This is illustrated in Table 1 where the effects of DF from wheat bran, corn bran and sugar beet pulp are compared. Detailed information on the effect of origin of DF on DCe in both growing pigs and adult sows has been given by Noblet and Le Goff (2001). These results indicate that growing pigs have a limited ability to digest DF with small differences between fiber sources while adult sows digest more efficiently DF but the improvement depends on the chemical characteristics of DF (e.g., level of lignin). The examples presented in Table 4 also illustrate the effect of botanical origin with small differences between physiological stages for Graminae (wheat, barley, wheat bran), Brassicaceae (rapeseed) or Compositae (sunflower) and more pronounced differences for Leguminosae (pea, soybean, lupin), especially for the hull fraction of these grains. The consequence is that the DE difference between adult sows and growing pigs is proportional to indigestible organic matter in growing pigs, but with specific coefficients for each (botanical) family of ingredients (Table 4; Figure 1; Noblet and Tran, 2004).

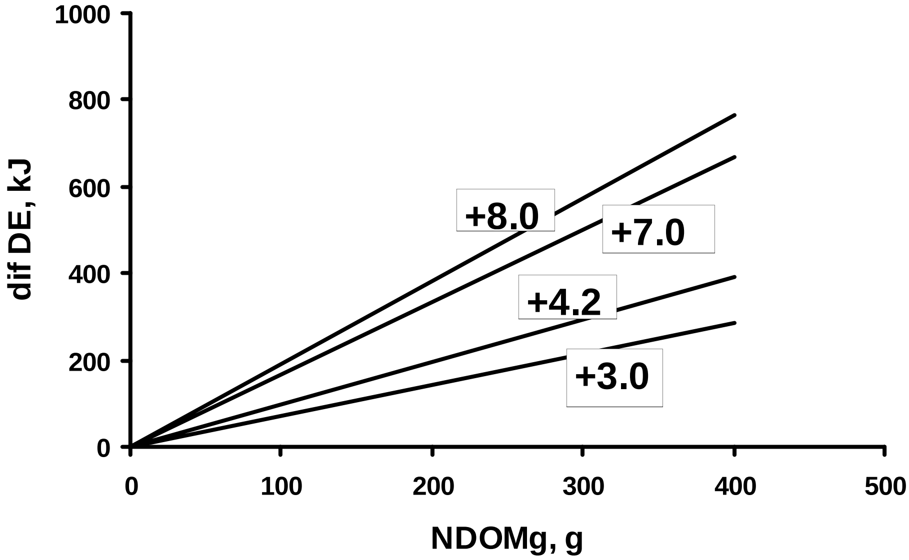
Table 4: Digestible energy value of some ingredients for growing pigs and adult sows[a]

Ingredient	DE, MJ/kg[b] Growing pig	DE, MJ/kg[b] Adult pig	a[c]
Wheat	13.85	14.10	3.0
Barley	12.85	13.18	2.5
Corn	14.18	14.77	7.0
Pea	13.89	14.39	6.0
Soybean meal	14.73	15.61	8.0
Rapeseed meal	11.55	12.43	3.5
Sunflower meal	8.95	10.25	3.5
Wheat bran	9.33	10.29	3.0
Corn gluten feed	10.80	12.59	7.0
Soybean hulls	8.37	11.46	8.0

[a] Adapted from Sauvant et al. (2004)
[b] As fed.
[c] kJ difference in DE between adult sows and growing pigs per g of undigestible organic matter in the growing pig (Noblet et al., 2004).

Recent results indicate that DCe in sows is little affected by feeding level (Noblet et al., 2003), which means that values obtained in pregnant sows fed approximately 2.5 kg per day can be extrapolated to lactating sows offered feed ad libitum. An indirect comparison between lactating sows fed above 5

Figure 1: Relationship between DE value in adult sows and DE value in growing pigs (dif DE) and undigestible organic matter in growing pigs (NDOM) for some families of ingredients (adapted from Noblet et al., 2003)



kg/day and pregnant sows fed 2.4 kg per day suggests the same conclusion (Noblet et al., 2003). Little information concerning comparative digestibility in piglets and growing pigs is available. Considering that piglets are usually fed low-fiber diets for which the effect of BW is minimized, piglets can, from a practical point of view, be considered as growing pigs concerning the digestive utilization of energy.

A consequence of the changes of DCe with BW is that digestibility trials should be carried out at approximately 60 kg BW (Noblet et al., 2003) in order to be representative of the total growing-finishing period. A second consequence is that at least two different DE values should be given to feeds: one for growing pigs and one for adult sows (Table 4; Sauvant et al., 2004). This proposal is more justified for fibrous ingredients.

ME:DE ratio

The ME content of a feed is the difference between DE and energy losses in urine and gases (i.e., as methane and hydrogen). In growing pigs, average energy loss in methane is equivalent to 0.4% of DE intake (Noblet et al., 1994). In sows fed at maintenance level, methane production represents a much greater proportion of DE intake (1.5%; Noblet and Shi, 1993) and may reach up to 3% of DE intake in sows fed very high fiber diets (Ramonet et al., 2000). More generally, methane production increases with BW and DF level in the diet. From the compilation of literature data conducted by Le Goff et al. (2002) and unpublished data from our laboratory, Noblet et al. (2004) proposed that methane energy is equivalent to 0.67 and 1.33 kJ per g of fermented DF in growing pigs and adult sows, respectively. Unlike humans, hydrogen production in pigs is rather low and can be neglected.

Energy loss in urine represents a variable percentage of DE since urinary energy depends greatly on the urinary nitrogen excretion. At a given stage of production, urinary nitrogen excretion depends mainly on the (digestible) protein content of the diet. Consequently, the ME:DE ratio is linearly related to the dietary protein content (Table 2). In most situations, the ME:DE ratio of complete feeds is approximately 0.96. However, this mean value cannot be applied to single feed ingredients (Noblet et al., 1993). Consequently, equation 3 in Table 2 cannot be applied beyond the range of typical CP contents of pig diets (10 to 25%) and is therefore not applicable for most ingredients. The most appropriate solution is then to estimate urinary energy (kJ/kg DM intake) from urinary nitrogen (g/kg DM intake). The following equations have been proposed:

Urinary energy in pigs = 192 + 31 x Urinary nitrogen
Urinary energy in sows = 217 + 31 x Urinary nitrogen

for growing pigs and adult sows, respectively. For implementing these equations to feed ingredients, it can be assumed that urinary nitrogen represents 50% of digestible nitrogen (Noblet et al., 2003, 2004).

Metabolic utilization of ME

Net energy is defined as ME minus heat increment associated with metabolic utilization of ME and to the energy cost of ingestion, digestion and some physical activity. It is generally calculated as the sum of (estimated or measured) fasting heat production and retained energy. The NE content, as a percentage of ME content (k) corresponds to the efficiency of utilization of ME for NE (Noblet et al., 1994). Apart from variations due to the final utilization of ME (e.g., maintenance, protein gain vs. fat gain vs. milk production), k varies according to the chemical characteristics of the feed since nutrients are not used with the same efficiencies (Noblet et al., 1993, 1994). The variations in k are due to differences in efficiencies of ME utilization between nutrients with the highest values for fat (~90%) and starch (~82%) and the lowest (~60%) for DF and crude protein. These values were confirmed in recent trials (van Milgen et al., 2001; unpublished data). These differences in efficiencies between nutrients also mean that heat increment (per unit of energy) associated with metabolic utilization of energy is higher for crude protein and DF than for starch or ether extract (Noblet et al., 1994; Table 5). Finally, NE measurements conducted in pigs which differ for their BW and the composition of BW gain suggest that the efficiency of ME for NE is little affected by the composition of BW gain, at least under most practical conditions. Similarly, the ranking between nutrients for efficiencies is similar in adult sows fed at maintenance level and in lean fast growing pigs.

Table 5: Energy value of starch, crude protein and fat according to energy systems[a]

	Starch	Crude protein[b]	Crude fat[b]
Energy values, kJ/g[b]			
Digestible energy	17.5 (100)	20.6 (118)	35.3 (202)
Metabolizable energy	17.5 (100)	18.0 (103)	35.3 (202)
Net energy	14.4 (100)	10.2 (71)	31.5 (219)
Heat production, kJ/g	3.1	7.8	3.8

[a] Adapted from Noblet et al. (1994) (n = 61 diets)
[b] Between brackets, energy values as % of starch; crude protein and crude fat are assumed to be 90% digestible; starch is 100% digestible.

The comparison of our results on ME utilization with literature data and the practical consequences on energy evaluation system have been reviewed by Noblet (2000) and Noblet and van Milgen (2004). They have also been validated in recent experiments conducted in our laboratory (Ramonet et al., 2000; van Milgen et al. 2001). They confirm that the increase of dietary crude protein results in an increased HP (Table 6). On the other hand, inclusion of fat contributes to reduction of HP. Diets with low crude protein and/or high fat contents can then be considered as low heat increment diets and are potentially better tolerated under conditions of heat stress (Renaudeau et al., 2001; Le Bellego et al., 2002). However, the effect of DF on HP remains unclear (Noblet and Le Goff, 2001). In some trials, HP is significantly increased when DF is increased (Noblet et al., 1993; 1994; Ramonet et al., 2000; Rijnen et al., 2003) while in other trials, HP remains constant or even decreases (Rijnen et al., 2001; Le Goff et al., 2002). From a biochemical perspective, HP should increase and most results are consistent with this. However, addition of DF may change the behavior of animals (i.e., reduced physical activity) or the overall metabolism, thereby decreasing HP. Furthermore, the effects of DF probably also depend on the nature of DF, and the specific effect of sugarbeet pulp DF (Rijnen et al., 2001) cannot be generalized to other DF sources. Differences in the design of trials and limits of methodologies may also explain these discrepancies. Finally, another interesting aspect illustrated in the results of van Milgen et al. (2001) concerns the HP associated to the utilization of dietary protein either for protein deposition or for lipid deposition. The data show that the heat increment associated with both pathways is similar and efficiencies are equivalent. From a practical point of view, this means that the NE value of dietary CP is constant, irrespective of its final utilization.

Table 6: Energy utilization of low protein diets

	Trial 1[a]		Trial 2[b]	
Crude protein, %	17.4	13.9	21.9-17.4	17.2-12.7
Digestible lysine, g/MJ NE	0.76	0.76	1.05-0.72	1.05-0.72
Energy balance, MJ/kg $BW^{0.60}$				
ME intake	2.46	2.46	2.57	2.57
Heat production	1.42^{x}	1.37^{y}	1.40^{x}	1.34^{y}
Energy retained	1.05^{x}	1.09^{y}	1.17^{x}	1.23^{y}
ME/DE, %	95.5^{x}	96.7^{y}	95.7^{x}	96.7^{y}
NE/ME, %	73.2^{x}	75.3^{y}	73.9^{x}	75.9^{y}

[a] From Le Bellego et al. (2001); 65-kg pigs; wheat, corn and soybean meal based diets; the low protein diet was supplemented with HCl-lysine (0.43%), methionine (0.11%), threonine (0.16%), tryptophan (0.05%), isoleucine (0.04%) and valine (0.09%); indirect calorimetry method was used for measuring heat production.

[b] From Noblet et al. (2003); in 25, 55 and 85 kg pigs; wheat, corn and soybean meal based diets; indirect calorimetry method was used for measuring heat production. Values for CP and lysine levels are given for the 25 and 85 kg pigs; values at 55 kg were intermediary.

[x,y] Values are significantly different ($P<0.05$) if different exponents are indicated (within trial).

Energy systems

Digestible and metabolizable energy

Apart from direct measurement on pigs, the DE and ME values of raw materials can be obtained from feeding tables (NRC, 1998; Sauvant et al., 2004). But the utilization of these tabulated values should be restricted to ingredients having chemical characteristics similar or close to those in the tables. As illustrated in the previous section, DCe is affected by BW of the animals. It is therefore appropriate to use DE and ME values adapted to each BW class. However, from a practical point of view, it is suggested to use only two values, one for "60 kg" pigs which can be applied to piglets and growing-finishing pigs and one for adult pigs applicable to both pregnant and lactating sows. Values given in most feeding tables are typically obtained in the 40- to 60-kg pig. The INRA & AFZ feeding tables (Sauvant et al., 2004) provide DE and ME values for these two stages and an illustration is given in Table 4.

The DE content of compound feeds can be obtained by adding the DE contributions of ingredients and assuming no interaction, which is usually the case (Noblet and Shi, 1994; Noblet et al., 2003a). When the actual composition of the feed is unknown, the possibility is to use prediction equations based on chemical criteria (Le Goff and Noblet, 2001) or estimates from near infrared or in vitro methods. Such equations cannot be used for feed ingredients.

Net energy

All published NE systems for pigs combine the utilization of ME for maintenance and for growth (Noblet et al., 1994) or for fattening by assuming similar efficiencies for maintenance and energy retention. The system used in the Netherlands has been adapted from the equations proposed by Schiemann et al. (1972). The "system" used by NRC (1998) for estimating NE values combines results from direct measurements using a questionable animal model (piglet) and estimates from prediction equations. The available NE systems have been described by Noblet (2000). More recently, Boisen and Verstegen

(1998) proposed new concepts for estimating the NE value of pig feeds (so-called physiological energy) and based on the combination of in vitro digestion methods for estimating digestible nutrients and biochemical coefficients for evaluating the ATP potential production from the nutrients. Complementary and theoretical knowledge concerning endogenous secretions could also be included in this approach. Apart from difficulties for implementing the in vitro digestion methods, this approach assumes that energy is used exclusively for ATP production - which is not the case in growing pigs, for instance.

The system proposed by Noblet et al. (1994) and applied in the INRA & AFZ feeding tables (Sauvant et al., 2004) is based on a large set of measurements (61 diets). These results have been validated in recent trials (Le Bellego et al., 2001; Noblet et al., 2001; van Milgen et al., 2001) and its applicability for predicting performance of animals has been demonstrated (see last section). The equations used for predicting NE are given in Table 7. They are all based on information available in conventional feeding tables and are applicable to single ingredients and compound feeds and at any stage of pig production. It has also been demonstrated that these equations can determine a correct hierarchy between feeds for both growing pigs and pregnant or lactating sows. It is important to point out that different DE values or digestible nutrient contents should be used in growing-finishing pigs and adult sows with two subsequent NE values. Reliable information on digestibility of energy or of nutrients is then necessary for prediction of NE content of pig feeds. In fact, this information represents the most limiting factor for predicting energy values of pig feeds.

Table 7: Equations for prediction of net energy in feeds for growing pigs (NEg; MJ/kg dry matter; composition as g per kg of dry matter).

Equation[a]	RSD,%	Source[b]
NEg2a = 0.0113 x DCP + 0.0350 x DEE + 0.0144 x ST + 0.0000 x DCF + 0.0121 x DRes	2.0	1
NEg2b = 0.0121 x DCP + 0.0350 x DEE + 0.0143 x ST + 0.0119 x SU + 0.0086 x DRes	2.4	2
NEg4 = 0.703 x DE - 0.0041 x CP + 0.0066 x EE - 0.0041 x CF + 0.0020 x ST	1.7	1
NEg7 = 0.730 x ME - 0.0028 x CP + 0.0055 x EE - 0.0041 x CF + 0.0015 x ST	1.6	1

[a] CF: Crude Fiber, CP: crude protein, EE: ether extract, ST: starch, DCP: digestible CP, DEE: digestible EE, DCF: digestible CF, DRes: digestible residue (i.e., difference between digestible organic matter and other digestible nutrients considered in the equation). The NEg suffix corresponds to the equation number, as given by Noblet et al. (1994).
[b] 1: Noblet et al. (1994); 2: Noblet et al. (2004).

INRA-AFZ feeding tables

The INRA-AFZ feeding tables (Sauvant et al., 2004) provide DE, ME and ME values of feeds for pigs as well as digestibility coefficients of major nutrients and organic matter. A lot of effort was put into the estimation of reliable NE values, as it is now agreed that NE content is the best assessment of the "true" energy value for pigs. Two companion articles to the INRA-AFZ tables were produced later on (Noblet et al., 2003; Noblet and Tran, 2004). An Excel spreadsheet has also been produced in order to make available all the equations that were used in the preparation of energy values that are presented in the feeding tables. It must be stressed that the energy values for energy and digestibility coefficients have been obtained only from literature values, thus excluding a "copy/paste" of previous feeding tables. The concepts used originate from studies conducted at INRA over the last 20 years.

Estimation of the energy value of feed ingredients for pigs requires several steps. The first one is the estimation of gross energy (GE); equations are proposed in the tables and in the Excel spreadsheet. In a second step, digestible energy (DE) is calculated as GE multiplied by the apparent faecal digestibility coefficient for energy (DCe). The energy losses in urine are calculated using the amount of nitrogen excreted in the urine and the losses in the form of gas from degraded cell walls. The metabolizable energy content (ME) is the difference between the DE value and the energy losses in urine and gas. The net energy (NE) value is estimated using the equations proposed by Noblet et al. (1994) that can be applied to both the growing pig and the adult sow. Details on the methods and the calculations for getting the values reported in the tables are given by Noblet et al. (2003; 2004) and Noblet and Tran (2004).

Ingredients presented in the feeding tables have a fixed composition and a corresponding energy value. However, the ingredients composition can be variable in practice, especially for by-products with expected variations in energy values. The basic approach cannot be used routinely for energy evaluation of such feed materials and simplified methods have then been proposed (Noblet et al., 2003; Noblet and Tran, 2004). In brief, for prediction of DE in growing pigs (DEg), prediction equations of GE and DCe have been produced per family of ingredients (Noblet et al., 2003; Noblet and Tran, 2004) and they can be applied for adjusting the DE value according to chemical composition; usually, dietary fiber criteria are used for that correction. For estimating DE in adult pigs (DEs) from DE in growing pigs (DEg), the DEs/DEg ratio cannot be considered as constant when the chemical composition of an ingredient differs from the one in the tables. The following formula:

$$\text{DEs / DEg, \%} = 100 + (a / 100) \times (100 - \text{Ash}) \times (100 - b \times \text{DCe}) / \text{Deg}$$

has been proposed in which "a" represents the amount of additional DE in adult pigs per g of undigestible organic matter in growing pigs (Table 4) and "b" the ratio between organic matter digestibility and energy digestibility. Ash content is in % of dry matter and DCe in %; DEg is expressed in MJ/kg of dry matter. Values of "a" and "b" are listed in the spreadsheet.

The ME/DE ratio of a feed material, for an average catabolism rate of proteins, is assumed to be constant when its chemical composition (nitrogen content) changes within reasonable limits. It is then possible to simplify the estimation of ME content of feed materials by calculating it as DE x (ME/DE). Values for ME/DE of feed materials are listed in the Excel spreadsheet (Noblet and Tran, 2004) or can be obtained from the INRA-AFZ tables per family of ingredients. Like the ME/DE ratio, the NE/ME ratio for a given ingredient does not vary much with the chemical composition. The NE can then be calculated as ME x (NE/ME). Values for NE/ME ratio are listed in the spreadsheet (Noblet and Tran, 2004).

Energy requirements

Energy requirements are expressed on different bases. In ad libitum fed pigs, they mainly consist in fixing the diet energy density according to regulation of feed intake (appetite), growth potential, climatic factors or economical conditions. In restrictively fed growing pigs or in reproductive sows, it is necessary to define feeding scales according to expected performance (dose response approach). Finally, in more sophisticated or more theoretical approaches (factorial approach or modelling approach), it is necessary to determine the components of energy requirements (requirements, growth, milk production, thermoregulation, etc). Whatever the level of approach, most trials and recommendations were conducted according to DE and ME estimates of feeds and conclusions were expressed as DE or ME values. In addition, the recommendations were obtained with rather conventional feeds, i.e. cereals-soybean meal based diets whose efficiency of ME utilization in growing pigs is close to 74%. This latter value also corresponds to the average efficiency obtained over 61 diets by Noblet et al. (1994). The proposal is then to estimate the NE recommendations (diet energy density, daily energy requirements, components of energy requirements, etc.) as DE or ME requirements multiplied by 0.71 or 0.74, respectively. In the case of reproductive sows, the same approach and the same "correction factors" can be used for estimating their NE requirements but with dietary energy values calculated according to NE values estimated for adult pigs. Finally, for factorial approaches, NE for maintenance can be estimated as 750 kJ/kg $BW^{0.60}$ and 320 kJ/kg $BW^{0.75}$ in growing pigs (Noblet et al., 1994; Le Bellego et al., 2001) and reproductive sows (Noblet et al., 1993), respectively. The NE requirement for growth or milk production is equal to the amount of retained or exported energy.

Comparison of energy systems

DE, ME and NE systems

From the equations reported in Tables 2 and 7, it is obvious that the hierarchy between feeds obtained in the DE or ME systems will vary in the NE system according to the specific chemical composition. Since NE represents the best compromise between the feed energy value and energy requirement of the animal, the energy value of protein or fibrous feeds will be overestimated when expressed on a DE (or ME) basis. On the other hand, fat or starch sources are underestimated in a DE system (Noblet et al., 1993). These conclusions are more clearly demonstrated in Table 8 for a series of ingredients: high fat (animal or vegetable fat, oil seeds) or high starch (tapioca, cereals) ingredients are penalized in the DE system while protein rich and/or fiber rich (meals, fibrous by-products) ingredients are favored. For mixed ingredients, the negative effect of protein or fiber (i.e., protein sources) on efficiency of DE or ME for NE is partly counterbalanced by the positive effect of starch or fat (i.e., energy sources).

Table 8: Relative digestible, metabolizable and net energy values of ingredients for growing pigs[a]

	DE	ME	NE	NE/ME[b]
Animal fat	243	252	300	90
Tapioca	101	103	110	81
Corn	103	105	112	80
Rapeseed (full-fat)	160	162	168	78
Wheat	101	102	106	78
Barley	94	94	96	77
Diet	100	100	100	75
Pea	101	100	98	73
Soybean (full-fat)	116	113	108	72
Wheat bran	68	67	63	71
Soybean meal	107	102	82	60
Rapeseed meal	84	80	64	60
Amino acids mixture	148	142	146	78

[a] Within each system, values are expressed as percentages of the energy value of a diet containing 67.4% wheat, 16% soybean meal, 2.5% fat, 5% wheat bran, 5% peas, 4% minerals and vitamins and 0.10% of HCl-lysine; the so-called amino acids mixture contains 50% HCl-lysine, 25% threonine and 25% methionine. From Sauvant et al. (2004)
[b] As %

Net energy systems

As explained above, several equations (and therefore systems) for prediction of NE of feeds are available (Schiemann et al., 1972: NEs; Just, 1982: NEj; Noblet et al., 1994: NEg; CVB, 1994: NEnl). The proposal of NRC (1998) cannot really be considered as a system. These systems were established according to different hypotheses and under different experimental conditions. Therefore, different NE systems do not provide interchangeable estimates and the NE value depends on the choice of the system. For comparing these NE systems, the measured NEg values of 61 diets (Noblet et al., 1994) have been compared to their calculated NEs, NEj and NEnl values. Comparison with the system proposed by Boisen and Verstegen (1998) was not possible at this stage. If we consider NEg as the 100 basis, average NEs, NEj and NEnl are equivalent to about 94, 83 and 96. As explained by Noblet (2000), these average differences are mainly due to differences in estimates of the fasting heat production. However, this ratio also depends on diet composition. It is slightly decreased for NEs and NEnl when dietary starch content is increased, which means that starch sources are underestimated according to these systems. However, both NEg and NEnl provide relatively consistent energy values. With regard to NEj, the NEj/NEg ratio is decreased when starch and fat levels are increased and increased for higher levels of crude protein or dietary fiber. It can then be considered that the NEj system is close to a ME system and it is progressively replaced by new system in Denmark. Finally, recent trials in which NE value of pig diets has been measured in growing pigs (van Milgen et al., 2001; Le Bellego et al., 2001; Noblet et al., 2001; Le Goff et al., 2002) or in adult sows confirm the accuracy of the NEg system since measured NE values and predicted values according to equations presented in Table 7 were similar.

Energy systems and performance

In diet formulation, chemical and ingredient composition of diets for growing-finishing pigs and reproductive sows is manipulated in order to achieve 1) a minimum level of recommended dietary energy and 2) minimum ratios between lysine and energy, and 3) minimum ratios between essential amino acids and lysine (i.e., ideal protein). These criteria are more relevant to the characteristics of the animal (i.e., BW, genotype, physiological stage) or, in other terms, the nutritional requirements. The expression of nutritional values of feeds should be as consistent as possible with the expression of nutrient requirements. From that point of view, the most consistent expression of energy value and energy requirements is theoretically based on NE. In addition, apart from minimizing the cost of diets, an objective such as minimizing heat dissipation (in heat stressed animals, for instance) can be met when formulating on a NE basis. More generally, the quality of a nutritional evaluation system is given by its ability to predict the performance of the animals and independently of the diet composition (or specific effects of nutrients).

The data presented in Tables 9 and 10 illustrate the relationship between energy system and performance and confirm that NE as calculated according to Noblet et al. (1994a; 2004) is a better predictor of performance than DE or ME. In other words, the NE value is a satisfactory estimate of the energy value of feeds. On the other hand, DE or ME systems overestimate the energy value of high CP diets (Table 11) and underestimate the energy value of fat rich diets. In the specific case of low protein diets which are more and more recommended in order to reduce the impact of pig production on the environment (Le Bellego et al., 2002; Table 9), it is clear that their energy value is underestimated when formulated on a DE or ME basis (Table 11). This may explain the tendency of fatter carcasses when low protein diets are formulated on a DE basis: animals are in fact getting more energy than expected from DE supply (Table 9). This also illustrates the importance of formulation criteria for interpreting performance results and the risks of manipulating the composition of diets according to inaccurate or inappropriate nutritional criteria. The use of ileal digestible (or available) amino acids and NE are then highly recommended.

Table 9: Energy requirements of ad libitum fed growing-finishing pigs according to energy evaluation system)[a]

	Diet 1	Diet 2
Diet composition, %		
Crude protein	18.8	14.5
Starch	45.9	50.9
Fat	2.5	2.6
Energy intakes, MJ/d		
DE	38.9[a]	37.3[b]
ME	37.1[a]	36.1[b]
NE	27.6	27.5
Nitrogen excretion, g/kg BW gain	50.2[a]	30.9[b]

[a] Performance were measured between 30 and 100 kg at a temperature of 22°C; energy intakes are adjusted by covariance analysis for similar BW gain (1080 g/day) and carcass composition at slaughter; diets had the same ratio between digestible lysine and NE (0.85 and 0.70 g/MJ in the growing and finishing periods, respectively) and the ratios between essential amino acids and lysine were above recommended values; diet composition values represent the mean of the growing diet and the finishing diet. Adapted from Le Bellego et al. (2002).

Table 10: Performance of ad libitum fed growing-finishing pigs according to dietary fat supplementation: comparison of energy systems)[a]

	Performance	Relative performance			
Fat supplementation, %	0	0	2	4	6
Feed intake, g/d	2200	100	97.3	97.7	94.1
ME intake, MJ/d	29.7	100	100.0	103.3	102.1
NE intake, MJ/d	22.5	100	100.6	104.3	103.6
BW gain, g/d	737	100	100.5	105.7	106.1
Feed to BW gain:					
kg/kg	2.98	100	96.6	92.3	88.9
MJ ME/kg	40.2	100	99.6	97.8	96.5
MJ NE/kg	30.4	100	100.1	98.8	97.9

[a] Between 36 and 120 kg BW; in three successive periods; at each period, the protein:energy ratio (Digestible lysine to NE) was the same for all diets; the protein:energy ratio decreased over successive periods. Protein and energy values of diets (corn/soybean meal/choice white grease) were calculated according to Sauvant et al. (2004).

Table 11: Effect of dietary crude protein level on energy utilization (MJ/kg BW0.60) in growing pigs (adapted from Le Bellego et al., 2001b)[1]

	Diet 1		Diet 2
Diet composition, %			
Crude protein	17.4		13.9
Starch	45.0		52.2
At the same DE intake			
Heat production	1.415	**	1.374
Retained energy	1.041	**	1.109
At the same ME intake			
Heat production	1.418	**	1.371
Retained energy	1.051	**	1.098
At the same NEg intake			
DE intake	2.594	**	2.528
ME intake	2.488	**	2.452
Heat production	1.421	**	1.368
Retained energy	1.067	-	1.084

[1] In 65 kg pigs; diets had the same ratio between digestible lysine and NE (0.76 g/MJ) and ratios between essential amino acids and lysine were above recommendations for ideal protein (six amino acids were supplemented in diets 2 and 3). Energy balance results were adjusted by covariance analysis. **: P<0.01

Conclusions

In this review, we have demonstrated that energy value of pig feeds density can be measured according to different criteria (DE, ME or NE) and different systems for each criterion. The most advanced and practically applicable energy evaluation system appears the NE system proposed by Noblet et al. (1994) for which energy values of most ingredients used in pig diets are available (Sauvant et al., 2004); complementary methods have been proposed for evaluating any ingredient that differs in terms of chemical composition from those defined in feeding tables. In addition, these authors have proposed energy values that are different for growing and adult pigs. Technological treatment can also affect the energy value. Unfortunately, current information is insufficient to take this systematically into consideration; it should be an area for future research. This review also indicates that the relative energy density or the hierarchy between ingredients depends on the energy system (DE vs. ME vs. NE) with considerable variation between ingredients or compound feeds when either fat or crude protein contents deviates from values in standard diets. This has also consequences on results of least-cost formulation with tendencies for lower crude protein diets and higher fat contents when changing from DE to ME and to NE systems. From that point of view, using NE instead of DE or ME is a potential technique for attenuating the negative consequences of pig production on environment by reducing the nitrogen waste. Finally, it can be mentioned that measured or estimated DE, ME or NE values of feeds are indicators of the potential energy value of the feed for meeting the energy requirements of the animals that are dependent on a lot of animal or environment factors. The accuracy of the prediction becomes higher when moving from DE to ME and to NE.

Significant improvements in prediction of energy value of pig feeds will come from an improved knowledge of energy and nutrients digestibility, which depends on chemical characteristics of the feed, (bio)technological treatments, animal factors (body weight) and interactions between these factors. Since DF is the main factor of variation of digestive utilization of the diet, more emphasis should be given to routine techniques that identify the nutritional and physiological "quality" and the role of DF. Improving feed evaluation systems will eventually consist in using more mechanistic approaches based on a nutrient supply (i.e., glucose, amino acids, etc.) which are used for meeting requirements for ATP, protein synthesis, and fat synthesis by the animal. Modeling approaches are then essential for describing both digestion of nutrients and metabolic utilization of nutrients. Energy value (expressed as a caloric value) will then become an auxiliary variable of the model.

Summary

Feeds can be attributed different energy values according to, first, the step considered in energy utilization (DE: digestible energy, ME: metabolizable energy and NE: net energy) and, second, the method used for estimation at each step. Some of the most important dietary (chemical composition, technology) and animal (body weight) factors which affect digestive and metabolic utilization of energy in swine are reviewed. Results indicate that energy digestibility of feeds is negatively affected by dietary fiber content but the negative effect is attenuated with body weight increase. This suggests that feeds should be attributed DE values according to pig BW; in practice, at least two different DE values, one for growing-finishing pigs and one for reproductive sows are recommended. The energy digestibility of pig feeds can also be affected by feed processing (pelletting for instance). Metabolic utilization of ME is dependent on diet chemical composition with efficiencies higher for energy from fat (90%) or starch (82%) than from protein or dietary fiber (60%). The hierarchy between feeds is then dependent on the energy system with overestimation of protein rich feeds and underestimation of starch and/or fat rich feeds in the DE or ME systems. The NE system provides an energy value which is the closest to the "true" energy value of a feed; it predicts more accurately the performance of the pigs and allows implementing safely new feeding approaches.

Zusammenfassung

Der Energiewert eines Futters kann unterschiedlich bestimmt werden, erstens nach der Stufe der Energienutzung (DE: verdauliche Energie; ME: metabolische Energie; NE: Nettoenergie) und zweitens nach der Methode, die auf der jeweiligen Stufe angewandt wird. Die wichtigsten Faktoren im Futter (chemische Zusammensetzung, Technologie) und im Tier (Körpergewicht), welche die verdauliche und nutzbare Energie beim Schwein beeinflussen, werden dargestellt. Ergebnisse von Fütterungsversuchen zeigen, dass die verdauliche Energie mit steigendem Rohfaseranteil sinkt, dass dieser Effekt aber mit steigendem Körpergewicht abnimmt. Deshalb wird vorgeschlagen, für die Praxis unterschiedliche DE-Werte für Mastschweine und Sauen zugrunde zu legen. Die verdauliche Energie eines Futters kann auch durch die technologische Behandlung (z.B. Pelletieren) beeinflusst werden. Die Nutzbarkeit von ME hängt von der chemischen Zusammensetzung ab und ist für Fett (90%) und Stärke (82%) höher als für Protein oder Rohfaser (60%). Die Hierarchie verschiedener Futtermittel hängt vom jeweils benutzten Energiesystem ab und tendiert dazu, den Energiewert in proteinreichen Futtermischungen zu überschätzen und in fett- bzw. stärkereichen Mischungen zu unterschätzen. Das NE System kommt dem wahren Energiewert eines Futters am nächsten. Es erlaubt eine genauere Prognose des Wachstums von Mastschweinen und eine entsprechend sichere Futterformulierung.

Literature cited

Boisen, S., and M.W.A Verstegen, 1998. Evaluation of feedstuffs and pig diets. Energy or nutrient-based evaluation systems? II. Proposal for a new nutrient-based evaluation system. Acta Agric. Scand., section A, Anim. Sci. 48: 95-102.

CVB, 1994. Veevoedertabel. Gegevens over voederwarde verteerbaarheid en samenstelling. CVB, Lelystad.

Just, A., 1982. The net energy value of balanced diets for growing pigs. Livest. Prod. Sci. 8: 541-555.

Le Bellego, L., J. van Milgen and J. Noblet, 2001. Energy utilization of low protein diets in growing pigs. J. Anim. Sci. 79: 1259-1271.

Le Goff, G., and J. Noblet, 2001. Comparative digestibility of dietary energy and nutrients in growing pigs and adult sows. J. Anim. Sci. 79: 2418-2427.

Le Goff, G., J. van Milgen and J. Noblet, 2002. Influence of dietary fibre on digestive utilization and rate of passage in growing pigs, finishing pigs, and adult sows. Anim. Sci. 74: 503-515.

Noblet, J., 2000. Digestive and metabolic utilization of energy in swine: application to energy evaluation systems. J. Appl. Anim. Res. 17: 113-132.

Noblet, J., V. Bontems and G. Tran, 2003. Estimation de la valeur énergétique des aliments pour le porc. Prod. Anim. 16: 197-210.

Noblet, J., and M. Champion, 2003. Effect of pelleting and body weight on digestibility of energy and fat of two corns in pigs. J. Anim. Sci. 81 (Suppl. 1): 140.

Noblet, J., H. Fortune, X.S. Shi and S. Dubois, 1994. Prediction of net energy value of feeds for growing pigs. J. Anim. Sci. 72: 344-354.

Noblet, J., and G. Le Goff, 2001. Effect of dietary fibre on the energy value of feeds for pigs. Anim. Feed Sci. Technol. 90: 35-52.

Noblet J., and J. van Milgen, 2004. Energy value of pig feeds: Effect of pig body weight and energy evaluation system. J. Anim. Sci. 82 (13), E. Suppl., E229-E238. (http://www.asas.org/symposia/04esupp/E229.pdf)

Noblet, J., B. Sève and C. Jondreville, 2004. Nutritional values for pigs. In: Tables of composition and nutritional value of feed materials: pigs, poultry, cattle, sheep, goats, rabbits, horses, fish. D. Sauvant, J.M. Perez and G. Tran (Eds.). Wageningen Academic Publ., Wageningen and INRA Ed., Versailles, p.25-35.

Noblet, J. and X.S. Shi, 1993. Comparative digestibility of energy and nutrients in growing pigs fed ad libitum and adult sows fed at maintenance. Livest. Prod. Sci. 34: 137-152.

Noblet, J., X.S. Shi and S. Dubois, 1993. Metabolic utilization of dietary energy and nutrients for maintenance energy requirements in sows: basis for a net energy system. Br. J. Nutr. 70: 407-419.

Noblet J. and G. Tran, 2004. Estimation of energy values of feeds for pigs. Feed Mix 11 (4): 16-19. http://www.inapg.inra.fr/ens_rech/dsa/afz/tables/energy_pig.htm

NRC, 1998. Nutrient Requirements of Swine. 10th ed. Natl. Acad. Press, Washington, DC.

Ramonet, Y., J. van Milgen, J.Y. Dourmad, S. Dubois, M.C. MeunierSalaün and J. Noblet, 2000. The effect of dietary fibre on energy utilisation and partitioning of heat production over pregnancy in sows. Br. J. Nutr. 84: 85-94.

Renaudeau, D., N. Quiniou, and J. Noblet, 2001. Effect of high ambient temperature and dietary protein level on performance of multiparous lactating sows. J. Anim. Sci. 79: 1240-1249.

Rijnen, M.M.J.A., M.W.A. Verstegen, M.J.W. Heetkamp and J.W. Schrama, 2003. Effects of tow different dietary fermentable carbohydrates on activity and heat production in group-housed growing pigs. J. Anim. Sci. 81: 1210-1219.

Sauvant, D., J.M. Perez and G. Tran, 2004. Tables of composition and nutritional value of feed materials: pigs, poultry, cattle, sheep, goats, rabbits, horses, fish. D. Sauvant, J.M. Perez & G. Tran (Eds). Wageningen Academic Publishers, Wageningen and INRA Editions, Versailles.

Schiemann, R., K. Nehring, L. Hoffmann, W. Jentsch and A. Chudy, 1972. Energetische Futterbewertung und Energienormen. VEB Deutscher Landwirt-schaftsverlag, Berlin, 344 pp.

Skiba, F., J. Noblet, P. Callu, J. Evrard, and J.P. Melcion, 2002. Influence du type de broyage et de la granulation sur la valeur énergétique de la graine de colza chez le porc en croissance. Journ. Rech. Porcine Fr. 34: 67-74.

Van Milgen, J., J. Noblet and S. Dubois S., 2001. Energetic efficiency of starch, protein, and lipid utilization in growing pigs. J. Nutr. 131: 1309-1318.